AFWAL-TR-85-2060

Volume III On-Board Inert Gas Generator System (OBIGGS) Studies
Part 3 Aircraft OBIGGS Designs

VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

L. A. Desmarais, W. J. Yagle, A. F. Grenich
Boeing Military Airplane Company
P.O. Box 3707
Seattle, WA 98124

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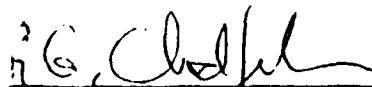Final Report for Period February 1981-October 1984

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R. G. Clodfelter, Chief
Fire Protection Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

FOR THE COMMANDER

R. D. SHERRILL, Chief
Fuels and Lubrication Division
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The primary performance of on-board inert gas generator systems (OBIGGS) in laboratory and simulated flight tests indicated these systems were suitable for aircraft implementation. Accordingly, preliminary design studies were made to determine the requirements for aircraft OBIGGS installations and to compare the OBIGGS with other fire protection systems. This report presents a technique for establishing the inert gas required for the design mission and discusses OBIGGS installations on a C-5B and an ATF airplane. Both permeable membrane (PM) and molecular sieve (MS) OBIGGS were considered for both airplanes. When all factors were considered the performance and penalties of the PM and MS OBIGGS on these airplanes was comparable. When compared with other fire protection systems, the OBIGGS had significant weight advantages over foam systems and significant cost and logistics advantage over Halon and liquid nitrogen systems.

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VULNERABILITY METHODOLOGY AND PROTECTIVE MEASURES FOR AIRCRAFT FIRE AND EXPLOSION HAZARDS

Volume III - On-Board Inert Gas Generator System (OBIGGS) Studies

Part 3 Aircraft OBIGGS Designs

This report is one of the set of aircraft fire protection reports contained in AFWAL-TR-85-2060 as listed below:

Volume I   Executive Summary

Volume II   Aircraft Engine Nacelle Fire Test Program

      Part 1 Fire Detection, Fire Extinguishment and Hot Surface Ignition Studies

      Part 2 Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III   On-Board Inert Gas Generator (OBIGGS) Studies

      Part 1 OBIGGS Ground Performance Tests

      Part 2 Fuel Scrubbing and Oxygen Evolution Tests

      Part 3 Aircraft OBIGGS Designs

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PREFACE

Aircraft fire protection research conducted by the Boeing Military Airplane Company under Contract F33615-78-C-2063 is discussed in this report. Most of the research was carried out in newly activated facilities, the Aircraft Engine Nacelle (AEN) simulator, and the Simulated Aircraft Fuel Tank Environment (SAFTE) simulator located at Wright-Patterson Air Force Base and was conducted between February 1981 and October 1984. The contract was sponsored by the Air Force Wright Aeronautical Laboratories (AFWAL) and the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). Guidance was provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSH), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 86. Gregory W. Gandee, Terrell D. Allen, and John C. Sparks were the Government project engineers.

The results are presented in three volumes with Volumes II and III subdivided into parts. Volume I summarizes the research conducted under this program, describes the test facilities used, and highlights important findings. Volume II discusses research related to *engine compartment (nacelle) fire* protection. Testing was done primarily in the AEN simulator, but some small scale testing was performed at Boeing facilities in Seattle. Volume III discusses fuel tank fire protection research studies performed under this contract. Most of this work was focused on on-board inert gas generator systems (OBIGGS). Much of the testing related to OBIGGS development was conducted in the SAFTE simulator, but again some related small scale testing was done in Seattle. The contents of the three volumes are listed below:

Volume I   Executive Summary

Volume II   Aircraft Engine Nacelle Fire Test Program

  Part 1   Fire Detection, Fire Extinguishment and Hot Surface Ignition Studies

  Part 2   Small Scale Testing of Dry Chemical Fire Extinguishants

Volume III <u>On-Board Inert Gas Generator System (OBIGGS) Studies</u>

Part 1   OBIGGS Ground Performance Tests

Part 2   Fuel Scrubbing and Oxygen Evolution Tests

Part 3   Aircraft OBIGGS Designs

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1.0 INTRODUCTION

Unacceptable aircraft losses to fires and explosions have prompted extensive studies on a variety of fire protection concepts. As military aircraft become more sophisticated and costly in real terms, protecting these valuable assets, as well as improving crew safety, are important considerations. Aircraft fuel tanks have been singled out for special attention because a significant percentage of aircraft fires and explosions are fuel tank related.

A number of fuel tank fire protection techniques have been proposed including:

o   providing an inert gas in the fuel tank vapor space (ullage);

o   filling the tank with a material that localizes fires and minimizes combustion generated overpressures;

o   locating fast acting fire detectors and extinguishant systems within the fuel tank; and

o   inerting the ullage with combustion gases or fuel vapors.

Although several techniques have been implemented, none have been totally satisfactory, as discussed below.

Installing explosion suppressant foam material in fuel tanks is designed to effectively localize in-tank fires and prevent damaging overpressures. This effectiveness has been demonstrated in fleet experience. However, the foam adds significant weight, reduces fuel volume, and greatly complicates fuel tank maintenance. Furthermore, operational problems surfaced as the aircraft gained fleet experience. The polyester foams (orange, red and yellow colored) sometimes suffered premature decomposition, allowing potentially hazardous voids to develop and small particles to be shed that had the potential to cause fuel filter clogging. Subsequently, longer life polyether foams (colored light and dark blue) were developed. However, these foams were more likely than polyester foams to produce incendiary electrostatic discharges as a result of refueling operations (Ref. 1) and inflight fuel movement. Although the foams prevent fuel tank explosions following electrostatic ignitions, the resulting low level fires may damage foam blocks in the immediate area. Locating and replacing these blocks is an expensive and time consuming process. Currently, foam materials are under study which combine

long life characteristics with sufficiently high electrical conductivity to prevent accumulation of electrostatic charges sufficient to produce an incendiary discharge.

Liquid nitrogen (LN_2) provides full time fuel tank inerting for the C-5 airplane (Ref. 2). Although this system is relatively light and simple, an LN_2 inerting system has one basic disadvantage, i.e., the airplane must be frequently resupplied with LN_2 (usually in conjunction with refueling). Since only a few airbases have cryogenic liquid handling capabilities, the LN_2 system has an inherent logistics disadvantage.

Halon fuel tank fire protection systems have been implemented to provide part-time protection when a hazardous condition can be anticipated. (Releasing Halon just prior to combat operations is a typical application of the part time protection concept.) The Halon system is simple and lightweight for small threats. For the 23mm HEI threat the Halon system would be much heavier but still lighter than the LN_2 system.

Optical detector/extinguishant systems have been investigated for fuel tank fire protection, but are usually impractical because of the large number of detectors required to obtain complete coverage of the multiplicity of compartments found in most airplane fuel tanks. The technique of fuel tank inerting using combustion products or fuel vapors has not been reduced to practical application.

The on-board inert gas generator system (OBIGGS) concept (Ref. 3) provides an attractive alternative to the above concepts for fuel tank fire protection. The OBIGGS processes high pressure air, such as engine bleed air, into an inert gas which eliminates the logistics problems of resupply of LN_2 and Halon systems. In addition, the OBIGGS has significant weight advantages over foam systems. Two OBIGGS concepts (Figure 1) have been shown to be feasible for aircraft installation. One concept uses a permeable membrane inert gas generator (PMIGG) to convert supply air into a nitrogen rich gas by exploiting the much greater membrane permeability to oxygen than nitrogen. The other OBIGGS concept utilizes a molecular sieve inert gas generator (MSIGG) which achieves nitrogen/oxygen separation by means of surface adsorption of oxygen within molecular sieve beds. Additional details of the PMIGG and MSIGG devices are included in Section 2.
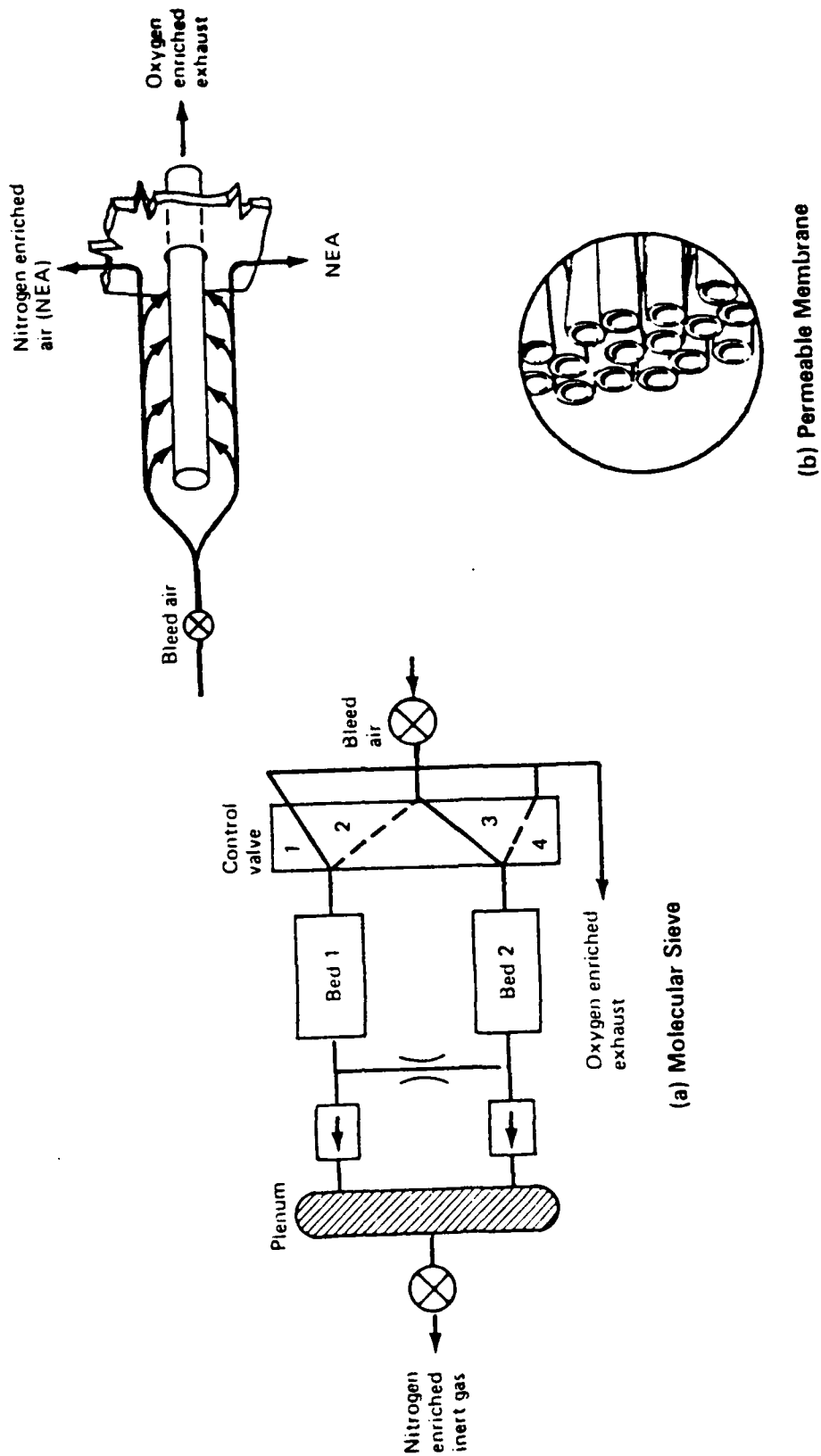
Figure 1. Air Separation Concepts

(a) Molecular Sieve

(b) Permeable Membrane

To examine the feasibility of OBIGGS for aircraft installations, preliminary designs were developed for the C-5B and an ATF airplane configuration and compared with other fuel tank fire protection concepts. The resulting designs and comparison studies are presented in Sections 3 and 4 respectively.

2.0 OBIGGS OPERATING PRINCIPLES AND AIRCRAFT DESIGN CONSIDERATIONS

Since the OBIGGS fuel tank inerting concept has a bleed air penalty as well as weight and volume penalties, tailoring the OBIGGS design to the aircraft mission requirements is quite important. Therefore, a discussion of the air separation process, inert gas requirements and appropriate design trades is presented prior to discussing actual airplane OBIGGS designs.

2.1 Inert Gas Generators

The PMIGG contains a multitude of hollow methyl pentene fibers, arranged in a cylindrical bundle around the hollow mandrel which distributes high pressure process air into the bundle. (Pressurizing the exterior rather than the interior of the fibers was found to significantly increase fiber life.) In operation, process air is distributed lengthwise through the fiber bundle by the perforated mandrel, and then flows radially outward through the bundle. Since oxygen permeates the membrane walls more readily than nitrogen, the gas inside the hollow tube membranes becomes oxygen rich and is discharged as waste gas. The gas which does not permeate the membrane is nitrogen rich and collected in the annular space around the fiber bundle to be used as the inert product gas. The principal control devices are a supply air pressure regulator and a choked flow orifice or a back pressure valve located in the inert gas (product) stream. The PMIGG is a steady flow system.

The MSIGG is based on pressure swing adsorption of oxygen with a minimum of two beds of synthetic zeolite sieve material. At high pressures, oxygen is preferentially adsorbed within the molecular sized pores of the sieve material. The pressure swing process begins with one bed pressurized to supply nitrogen rich gas which is collected at the downstream end of the bed. Simultaneously, the other bed is vented to the atmosphere, allowing the oxygen rich gas to be desorbed and vented overboard as waste gas. A small quantity of product gas is used to assist in purging the desorbing bed. The role of the beds alternates in a cyclic process from adsorption to desorption. As with the PMIGG the principal control devices are also a supply air pressure regulator and a choked flow orifice or a back pressure valve located in the product stream.

Complete separation of nitrogen and oxygen is not attempted in practical systems; the product gas contains some oxygen (and the waste gas some nitrogen). Both the product (inert) gas flow rate and the ratio of product gas to supply gas increase significantly with supply air pressure for both the PMIGG and MSIGG. Furthermore, the flow rate and oxygen concentration of the inert gas are directly related; as the inert gas flow rate is allowed to increase the oxygen concentration increases proportionately. The primary differences between the PMIGG and MSIGG are the inert gas yield per unit volume and per unit weight, considering the limitations of operating temperatures and pressures. These differences are very important in trade-off studies of inert gas generation capacity versus necessary conditioning of the supply air and the integration of the on-board inerting system with other aircraft subsystems. The system for conditioning the supply air is discussed in more detail later in the report.

Both the MSIGG and PMIGG units separate water vapor present in the process air and discharge it with the waste gas, resulting in extremely dry inert gas product flow.

2.2 Tailoring OBIGGS Designs To Aircraft Missions

OBIGGS sizing is based on a detailed analysis of aircraft mission requirements. Inert gas requirements for fuel scrubbing and ullage wash flow to control the rate of evolution of dissolved oxygen, and the inert gas required for descent repressurization, need to be evaluated. The mission with the most severe inert gas requirements will generally become the design mission. (The exception might be when the worst case mission is a very low probability event.) Once the design mission is established, an OBIGGS design, that satisfies the inert gas requirements while minimizing airplane penalties, is developed.

The goal of a full time fuel tank inerting system is to maintain a safe ullage by preventing the oxygen concentration from exceeding 9% by volume. This concentration limit is based on the results of many experiments (see Ref. 4) which revealed that sustained combustion is impossible with oxygen concentrations below 9%. The nitrogen enriched air (NEA) supplied by the OBIGGS to the fuel tanks must therefore have an oxygen concentration of 9% or

less. Maintaining these safe levels of oxygen concentrations in the fuel tank ullages requires the airplane to be designed with a closed vent system to prevent air from entering the fuel tanks and include nozzles for fuel scrubbing or ullage washing to manage oxygen evolution from the fuel.

Fuel scrubbing and/or ullage washing is required because significant quantities of oxygen may be added during refueling in the form of dissolved oxygen in the fuel. If the subsequent evolution of this dissolved oxygen is not managed properly, the ullage oxygen concentrations could increase beyond the safe limit. The quantity of dissolved gases in the fuel varies, but the design should be based on the worst case, i.e., fuel with dissolved gases in equilibrium with atmospheric gases at sea level. At equilibrium, atmospheric gases are dissolved in proportion to the partial pressures of the gases in their vapor phase. Due to the differences in solubility of oxygen and nitrogen (ignoring trace atmospheric gases), about 35% of the dissolved gases are oxygen and 65% are dissolved nitrogen in equilibrium at sea level. As the tank pressure decreases during airplane climbout in response to decreasing ambient pressure, the partial pressures of the oxygen and nitrogen in the fuel tank ullage also decrease. Dissolved gases will then evolve from the fuel in proportion to the solubility of the gases. Without scrubbing or an initially inert ullage volume, the ullage oxygen concentration would increase from about 21% at sea level to about 34% at cruise altitude. An initially inert ullage volume is of some benefit, but when a fuel tank is filled to its minimum expansion space with air saturated fuel, the ullage could quickly exceed the 9% oxygen limit due to oxygen evolution.

The fuel scrubbing and ullage washing techniques can effectively control dissolved oxygen evolution such that a safe ullage is maintained. Fuel scrubbing involves bubbling inert gas through the fuel in the form of many tiny bubbles to displace dissolved oxygen. Ullage washing involves sweeping the ullage volume with an inert gas, carrying away evolved oxygen in the process, and expelling the gases from the airplane through the vent system. Generally, fuel scrubbing makes more efficient use of inert gas than ullage washing. However, this difference is not necessarily an advantage. The higher efficiency of the scrubbing process could produce an oxygen concentration in the ullage early in the scrubbing process which exceeds the 9% safe limit. This factor illustrates the importance of tailoring the OBIGGS design to the airplane mission.

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Fuel tank repressurization during descent is linked to the practical structural limits on tank overpressures or underpressures. At high altitudes (low ambient pressure) the ullage pressure must also be relatively low to prevent tank bursting. During a descent (increasing ambient pressures) the tanks must be pressurized at a rate which prevents excessive underpressures. The most severe demand on the OBIGGS usually accompanies a high speed descent from a high altitude with essentially empty fuel tanks. Trade-off studies have shown that inert gas generators sized to supply the flow rates required for tank repressurization during high speed descents could be unreasonably large. A better solution in some cases is a design which includes a gas storage system, composed basically of a compressor and a storage tank (accumulator); the tank provides a source of inertant flow at times of high demand inert gas flow rates. The storage tank would be resupplied during cruise or other times when the air separation modules have excess capacity.

In summary, sizing of the air separation modules and inert gas storage systems (if required) may depend either on managing dissolved oxygen evolution from the fuel or on the inert gas flow rate during a high speed descent. Whether the higher quality (lower oxygen concentration) NEA required for scrubbing and wash flow or the lower quality, higher flow rate NEA acceptable for descent repressurization sizes the inerting units depends on a detailed analysis of the specific mission profile.

2.3 OBIGGS Sizing

Since either the scrub gas (or ullage wash flow) requirement or the descent repressurization requirement may size the OBIGGS system, each requirement should be evaluated for the selected design mission and ground rules. Analytical results depend on key assumptions because of the complexity of the actual mixing and diffusion processes. Test data (see Volume III, Part 1 of this report) support the key assumptions used in the analytical techniques described below.

Fundamental to the calculation of OBIGGS performance is the relationship among air supply pressure, inert gas flow rate, oxygen concentration in the product gas, and the ambient or exhaust pressure for the waste gas for the air separation modules. Although there are some effects of scale, the inert gas flow rates of PMIGG and MSIGG systems can be determined for preliminary designs using a single set of curves normalized to supply air flow characteristics such as flowrate and pressure. Performance maps and correction curves for supply air temperature and exhaust pressure for actual PMIGG and MSIGG systems are shown in Figures 2 and 3 respectively. These data provide a basis for preliminary design sizing. The approach for final design would be similar but demand more complete performance maps with performance data at critical supply and exhaust conditions.

Since fuel tank inerting requires careful control of ullage pressure, the tank vent system must be a closed system; tank differential pressures are maintained within proper limits by climb and dive relief valves which prevent aircraft fuel tank damage during altitude changes. These valves open at various differential pressures depending on the airplane requirements and structural limits.

2.3.1 Fuel Scrubbing

The procedure for determining the inert gas scrub flow required to maintain a safe ullage during taxi and climb out is described in this section. An analytical model for computing ullage oxygen concentration as a function of scrub gas flow was developed for the standard scrubbing technique of introducing inert gas in the form of a multitude of small bubbles at the bottom of the fuel tank. As the bubbles rise upward through the fuel, the bubbles remove dissolved oxygen and add dissolved nitrogen to the fuel.

The analytic model is based on conventional gas mixture relationships, conservation equations, and the Ostwald coefficient (Ref. 5) for evaluating the quantity of dissolved gases versus time. (The Ostwald coefficient is the equilibrium ratio of the volume of dissolved gas in a unit volume of solution at the same pressure and temperature). The basic assumptions used in the fuel
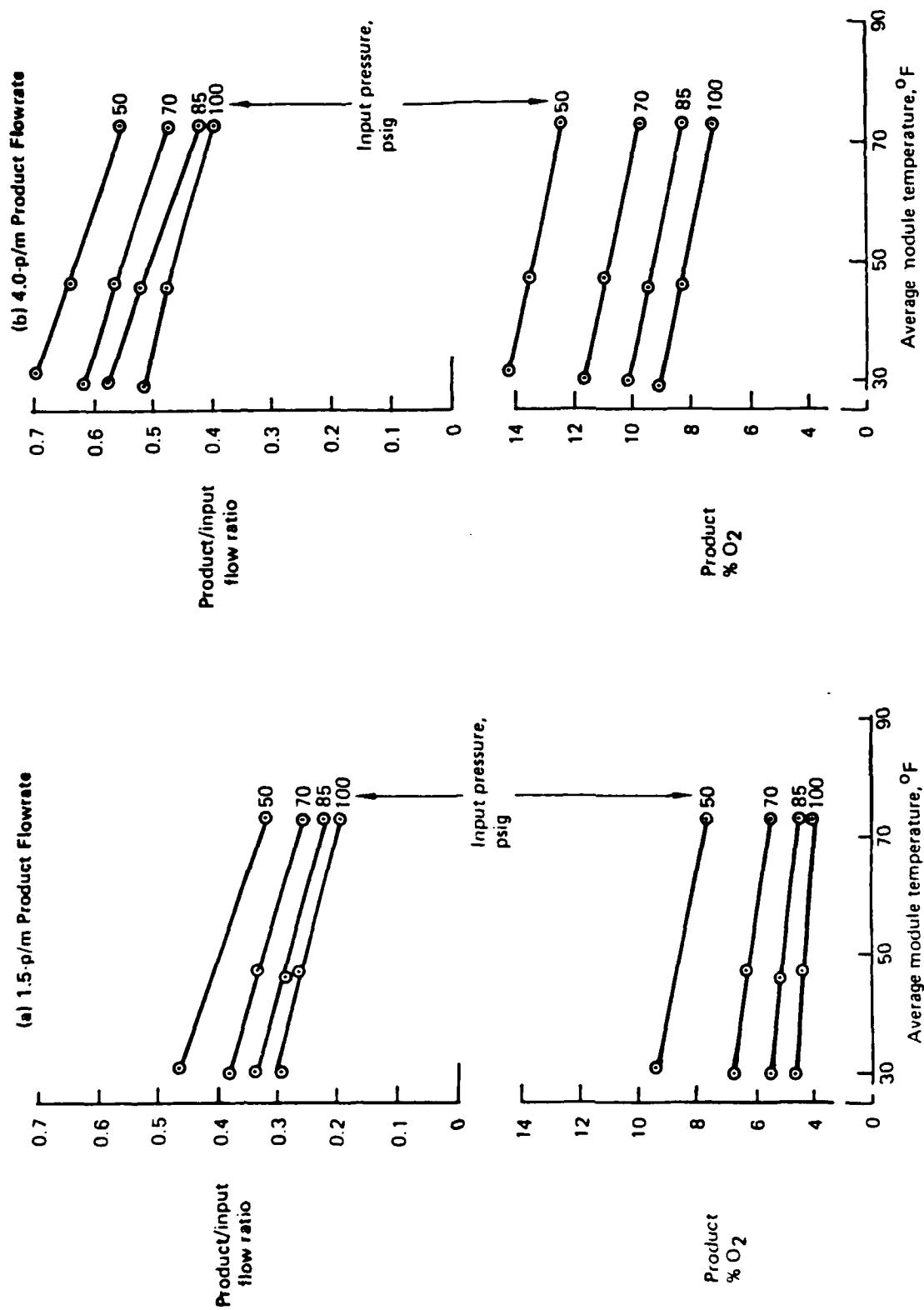
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Figure 2. Representative PMIGG Performance Data

Figure 2. Representative PM/GG Performance Data (Continued)

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Figure 2. Representative PMIGG Performance Data (Concluded)

Figure 3. Representative MSIGG Performance Data
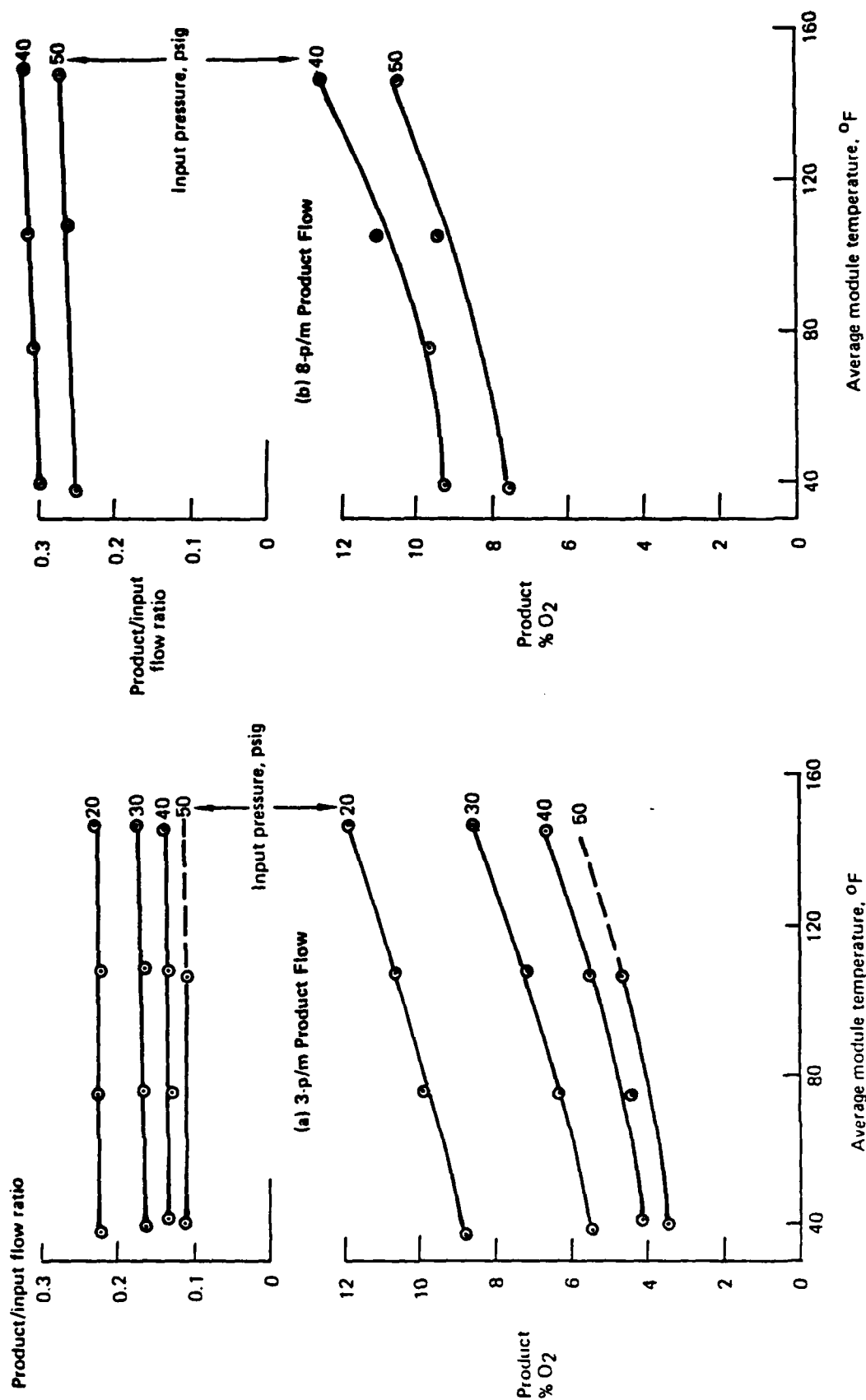
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Figure 3. Representative MSIGG Performance Data (Continued)

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Figure 3. Representative MSIGG Performance Data (Concluded)

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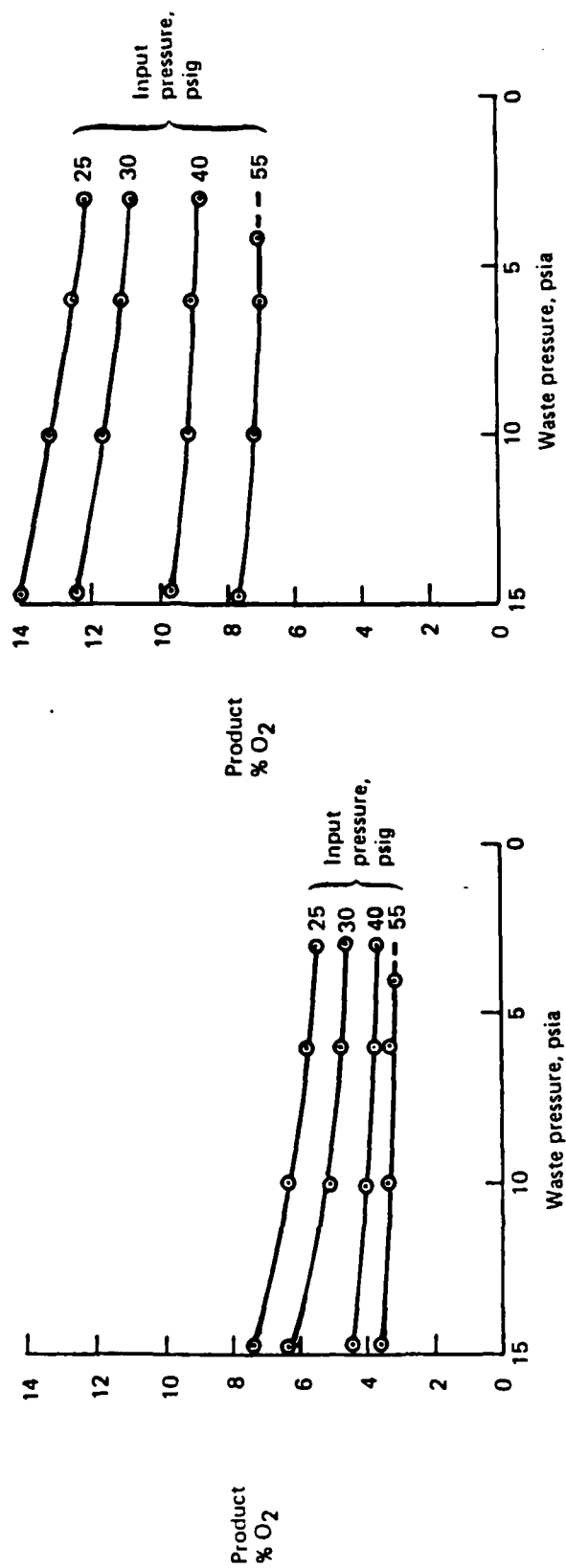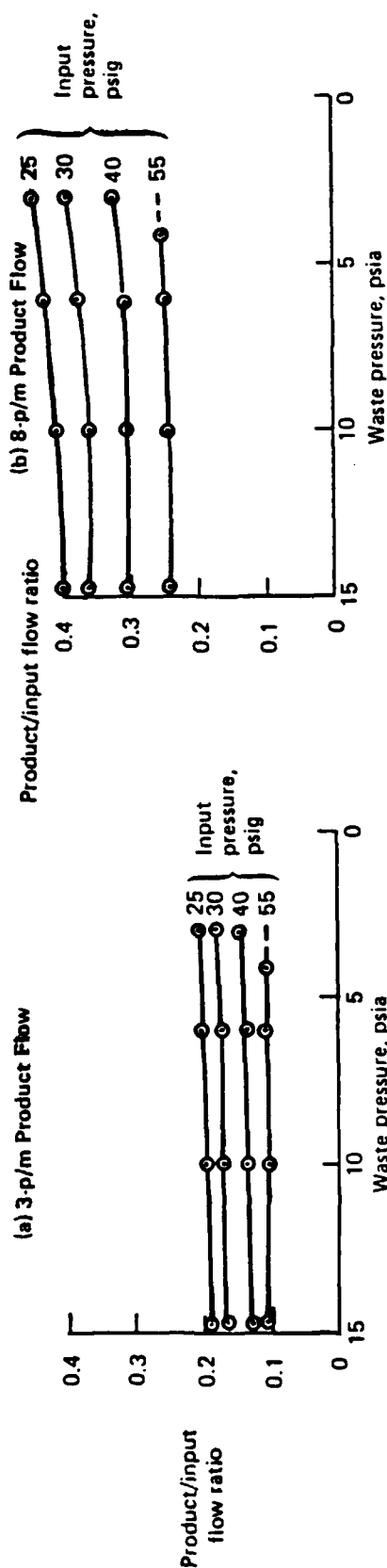
scrubbing model are:

- o A three component ullage gas model is valid, consisting of oxygen, nitrogen and fuel vapor.
- o The ideal gas law establishes oxygen and nitrogen ullage gas property relationships.
- o The Ostwald solubility coefficient varies linearly with temperature.
- o The scrub gas and fuel temperatures are equal.
- o The tank total pressure and fuel vapor pressure remain constant during time increments for scrubbing and venting proceses.

The resulting equations are solved using the standard approach of numerical integration using small time steps. Several initial and boundary conditions are required. Initial conditions include ullage gas composition, fuel temperature, and tank pressure. Time varying boundary conditions include fuel tank total pressure, fuel temperature (and ullage temperature, if different), scrub gas flow rate, and oxygen concentration and fuel vapor pressure as a function of fuel temperature.

The analytical approach is based on application of the equation for conservation of mass for a control volume to gas species of interest as follows:

$$\frac{\partial \mu}{\partial t})_{\substack{control \\ volume}} = \dot{\mu}_{IN} - \dot{\mu}_{OUT} \tag{1}$$

where

μ = mass of specie μ

$\dot{\mu}$ = mass flow rate of specie μ

t = time

and the subscripts are

IN = inflow

OUT = outflow

Using the fuel as the control volume and the finite difference approximation of Equation 1, the conservation of mass equations for oxygen and nitrogen become

$$\dot{O}_{F,IN} \, \Delta t + O_{F,1} = O_{F,OUT} + O_{F,2} \tag{2}$$

$$\dot{N}_{F,IN} \, \Delta t + N_{F,1} = N_{F,OUT} + N_{F,2} \tag{3}$$

where

O = mass of oxygen

$\dot{O}$ = mass flow rate of oxygen

N = mass of nitrogen

$\dot{N}$ = mass flow rate of nitrogen

and the subscripts are

F = fuel

1 = condition at start of time increment

2 = condition at end of time increment

Since the total pressure and fuel vapor pressure are constant during the compute interval, the partial pressure relationships may be written

$$P_{O,F,1} + P_{N,F,1} = P_{O,F,2} + P_{N,F,2} = P_t - P_v \tag{4}$$

where

P = pressure

and as subscripts

O and N refer to oxygen and nitrogen respectively

t = total condition

v = fuel vapor

The tank total pressure, P_t, is established by initial or boundary conditions; P_v is based on the fuel temperature at the start of the time increment. Since the evolved oxygen and nitrogen gases are assumed to be in equilibrium with the dissolved gases, the ideal gas law yields

$$P_{O,F,2} = \frac{O_{F,OUT}\, R_O\, T_F}{V_E} \tag{5}$$

$$P_{N,F,2} = \frac{N_{F,OUT}\, R_N\, T_F}{V_E} \tag{6}$$

Here

R = specific gas constant

T = temperature

V_E = equilibrium volume

The Ostwald relationship provides the relationship between the mass and partial pressure of dissolved gases, eliminating the equilibrium volume, V_E, in the process

$$O_F = \frac{\beta_O\, V_F\, P_{O,F}}{R_O\, T_F} \tag{7}$$

$$N_F = \frac{\beta_N\, V_F\, P_{N,F}}{R_N\, T_F} \tag{8}$$

where β is the Ostwald coefficient

Equations 2 through 8 are sufficient to establish all the unknowns. Of particular interest are the oxygen and nitrogen partial pressures at the end of the interval since they determine the quantity of gases evolved and the initial amounts of dissolved gases for the next compute step.

The next basic assumption is to assume that gases which evolve during scrubbing completely mix with the ullage gases prior to venting. The conservation of mass equations for the ullage can then be written

$$O_{U,mix} = O_{U,1} + O_{F, OUT} \tag{9}$$

$$N_{U,mix} = N_{U,1} + N_{F,OUT} \tag{10}$$

Where the subscript "mix" refers to the mixture of ullage gases. Again the ideal gas law is utilized as

$$O_{U,1} = \frac{P_{O,U,1} \, V_U}{R_O \, T_U} \tag{11}$$

$$N_{U,1} = \frac{P_{N,U,1} \, V_U}{R_N \, T_U} \tag{12}$$

Here the subscript U refers to the ullage; the ullage temperature, T_U, and volume, V_U, are specified as inputs. The total pressure of the ullage gas mixture, $P_{t, mix}$ prior to venting is calculated by

$$P_{t,mix} = P_v + \frac{O_{U,mix} \, R_O \, T_U}{V_U} + \frac{N_{U,mix} \, R_N \, T_U}{V_U} \tag{13}$$

Now $P_{t,mix}$ is compared with $P_{t,V}$ (vent outlet pressure defined by the mission profile ambient pressure and climb valve setting) to determine the amount of venting required. If $P_{t,mix} \leq P_{t,V}$, $P_{t,2}$ is set equal to $P_{t,mix}$; if $P_{t,mix} > P_{t,V}$, oxygen and nitrogen are vented in proportion to their mole fractions. The mole fractions of oxygen, X_O, and nitrogen, X_N, may be calculated by

$$X_{O,mix} = \frac{O_{U,mix} \, R_O \, T_U}{V_U} / P_{t,mix} \tag{14}$$

$$X_{N,mix} = \frac{N_{U,mix} \, R_N \, T_U}{V_U} / P_{t,mix} \tag{15}$$

Since the ratio of mole fractions and partial pressures are equal, the partial pressures in the ullage of oxygen, $P_{O,U,2}$, and nitrogen, $P_{N,U,2}$, at the end of the time increment may be obtained as follows

$$P_{N,U,2} = (P_{t,2} - P_v)/(\frac{X_{O,mix}}{X_{N,mix}} + 1) \tag{16}$$

$$P_{O,U,2} = P_{N,U,2} (X_{O,mix}/X_{N,mix}) \tag{17}$$

The foregoing procedure establishes all of the conditions at the end of the time increment allowing one to proceed to the next increment and, in particular, to define the ullage oxygen concentration from Equation 14.

2.3.2 Ullage Wash Flow

Although ullage washing generally makes less efficient use of the inert gas than fuel scrubbing, ullage washing may be a viable technique by itself for some applications or in conjunction with fuel scrubbing for other applications. In the ullage washing process, inert gas is injected into the ullage where it mixes with the existing ullage gases and gases evolved from the fuel; the resulting mixture then is vented overboard through the climb valve as required to satisfy the vent pressure boundary condition.

The analytic model for ullage washing is based on a finite difference technique and equations utilizing the inputs and assumptions discussed below:

Input Data:

- o Initial conditions
  - ullage gas composition
  - ullage gas temperature
  - fuel temperature
  - ullage gas pressure
  - ullage volume
  - fuel volume

o Boundary conditions (mission profile)
  • vent outlet pressure
  • fuel temperature
  • inert gas flow rate
  • inert gas composition
  • ullage gas temperature
  • ullage gas volume
  • fuel volume

Assumptions

o Oxygen and nitrogen gases are vented from the ullage in proportion to their mole fractions.

o The partial pressure of fuel vapor in the ullage depends only on fuel temperature.

o The solubilities of oxygen and nitrogen in the fuel are given by the Ostwald coefficient.

o Gas properties are defined by the ideal gas law

o Dissolved oxygen and nitrogen in the fuel immediately come to equilibrium in response to changes in the partial pressures of oxygen and nitrogen in the ullage. (Although the equilibration process may be far from instantaneous, especially for kerosene type fuels, the equilibrium assumption should produce conservative, i.e., upper limit, estimates of wash flow requirements).

Using these ground rules, one can write the following set of equations (using the same notation as for the scrub flow analysis):

$$O_{U,1} + \dot{O}_{U,IN} \Delta t + \Delta O_F = O_{U,2} + O_{U,OUT} \tag{18}$$

$$N_{U,1} + \dot{N}_{U,IN} \Delta t + \Delta N_F = N_{U,2} + N_{U,OUT} \tag{19}$$

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The changes in oxygen and nitrogen in the ullage due to fuel solubility can be expressed

$$\Delta O_F = \frac{\beta_O}{R_O} \left(\frac{P_{O,U,1} V_{F,1}}{T_{F,1}} - \frac{P_{O,U,2} V_{F,2}}{T_{F,2}} \right) \tag{20}$$

$$\Delta N_F = \frac{\beta_N}{R_N} \left(\frac{P_{N,U,1} V_{F,1}}{T_{F,1}} - \frac{P_{N,U,2} V_{F,2}}{T_{F,2}} \right) \tag{21}$$

The partial pressure relationships are

$$P_{t,1} = P_{O,U,1} + P_{N,U,1} + P_v \tag{22}$$

$$P_{t,2} = P_{O,U,2} + P_{N,U,2} + P_v \tag{23}$$

From the ideal gas law

$$P_{O,U,1} = \frac{O_{U,1} R_O T_{U,1}}{V_{U,1}}; \qquad P_{O,U,2} = \frac{O_{U,2} R_O T_{U,2}}{V_{U,2}} \tag{24}$$

$$P_{N,U,1} = \frac{N_{U,1} R_N T_{U,1}}{V_{U,1}}; \qquad P_{N,U,2} = \frac{N_{U,2} R_N T_{U,2}}{V_{U,2}} \tag{25}$$

Assuming oxygen and nitrogen are vented in proportion to their mole fractions

$$\frac{O_{U,OUT}}{N_{U,OUT}} = \frac{P_{O,U,2} R_N}{P_{N,U,2} R_O} \tag{26}$$

These equations allow conditions at state 2 to be established and in particular the oxygen concentration in the ullage through the ratio $P_{O,U,2}/P_{t,2}$.

2.3.3 Descent Repressurization

Inert gas repressurization flow required at the maximum descent rate will often size the inerting system. Whether the choice is for air separation modules sized to provide the maximum inert gas flow rate or an inert gas storage system will depend on the aircraft and its design mission.

Calculation of descent repressurization is straightforward, once a choice is made between assuming adiabatic or isothermal flow into the ullage. Although adiabatic flow requires less repressurization flow, this assumption is not recommended since the test data (see Volume III, Part I) show that the process is more nearly isothermal. The ullage temperature may be adjusted during the repressurization process based on a mass weighted average if the temperatures of the ullage gas and the inert gas are significantly different. Calculation of ullage pressure during descent is based on the initial conditions of ullage volume (assumed constant during descent), the ullage partial pressures of oxygen and nitrogen, the fuel vapor pressure (also assumed constant during descent), and the ullage gas temperature. The solution provides inert gas flow rate and gas temperature as a function of time. Following the notation used above, the ullage pressure, $P_{t,2}$, at the end of the selected time increment is given by the following equations:

$$P_{O,U,2} = P_{O,U,1} + \frac{R_O \, T_U}{V_U} \, (\dot{O}_{IN} \, \Delta t) \tag{27}$$

$$P_{N,U,2} = P_{N,U,1} + \frac{R_N \, T_U}{V_U} \, (\dot{N}_{IN} \, \Delta t) \tag{28}$$

$$P_{t,2} = P_{O,U,2} + P_{N,U,2} + P_v \tag{29}$$

Note that the flow rate of inert gas is composed of the oxygen and nitrogen flow rates consistent with the oxygen concentration in the nitrogen enriched air used for fuel tank repressurization. Note also that whether the inert gas flow rate is acceptable depends on the ullage pressure relative to the ambient pressure. If the flow rate is too low the dive valves would open, allowing air to enter the tanks. If the flow rate is larger than required, the size of the OBIGGS could probably be reduced.

2.4 Conditioning of Supply Air

The OBIGGS requires a source of high pressure air for proper operation. Engine bleed air is the most common source of high pressure air utilized as the energy source for air cycle based environmental control systems (ECS) and

other aircraft service requirements. Powerplant limitations on some aircraft may require that ram air or cabin air be used for the process air. Since OBIGGS performance is highly dependent on supply air pressure and temperature, this process air must be conditioned, compressed or pressure regulated, cooled, and cleaned to reasonable levels of moisture and particulate contamination.

Optimum supply air conditions and limitations vary between PMIGG and MSIGG systems. Furthermore, the trade between aircraft penalties resulting from extracting and conditioning the process air and the direct penalties of the inerting system will vary between the two approaches. For example, the PMIGG fiber life may degrade rapidly at combinations of high supply air pressure and temperature. Studies with current technology modules revealed that the supply pressure should be limited to the range of 80 to 85 psig when operating with supply temperatures in the optimum range of 75 $\pm 5^0$F. The MSIGG synthetic zeolite bed material does not have comparable limits based on the capability of the material to withstand the operating stress; the only pressure limits are the penalties of the supply system and the mechanical design features of the zeolite bed restraining system. The temperature limits are those associated with any valves and components as well as the general decay in performance at higher temperatures.

The following example illustrates the importance of considering the complete system when specifying supply air conditions. Tests on air separation modules sized for the KC-135 airplane revealed that although the PMIGG could produce the same inert gas flow as the MSIGG with significantly less supply air flow, the corresponding supply air pressure would be much higher. To achieve the high supply air pressure could involve auxiliary compressors and additional cooling which tends to offset the apparent higher efficiency of the PMIGG module.

A simple direct process air conditioning system is depicted in Figure 4. Engine bleed air is cooled by ambient air in an air-to-air heat exchanger and subsequently filtered to remove dust and other contaminants. A scupper type water extractor is used to remove any entrained water, and a pressure regulator is used to regulate engine bleed air pressures to values which ensure efficient IGG operation. The main disadvantage is the poor temperature control associated with operation in high ambient temperatures.
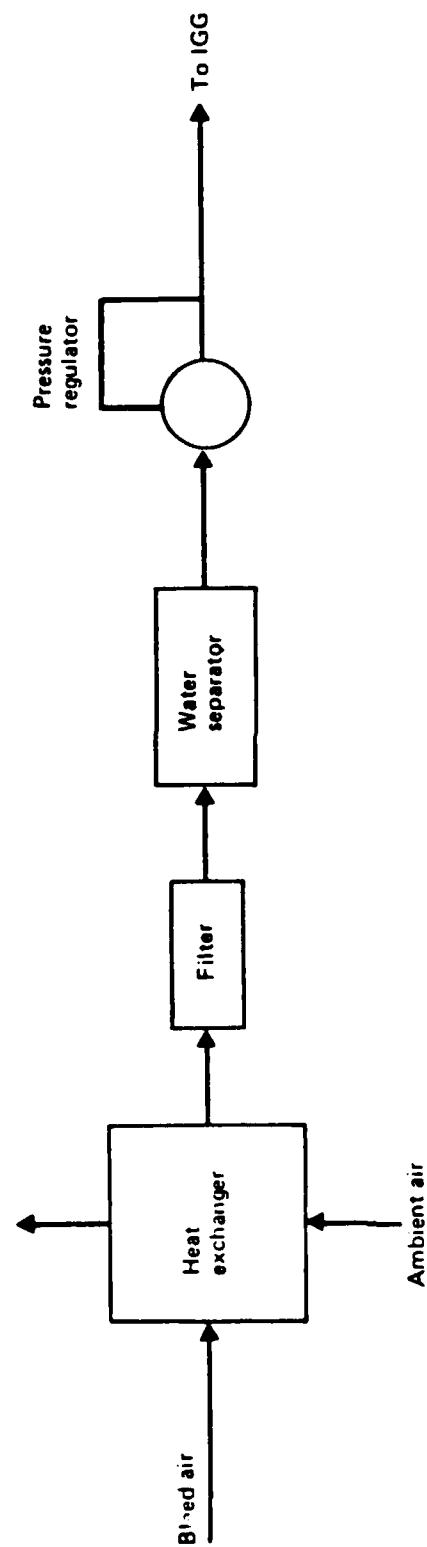
Figure 4. Direct Conditioning of Supply Air

A second process air conditioning system is depicted in Figure 5. The air source in this case might be a lower stage of compressor bleed or aircraft service air supplied by the ECS. The boost compressor is required to increase working pressure to acceptable levels under certain conditions (particularly during the descent conditions). The heat exchanger shown could be either air/air or air/liquid, depending on the cooling available from ECS or thermal management systems. The air filtration, water extraction, and pressure regulating functions are identical to those of Figure 4. This system achieves better control of the IGG process air at the expense of greater system complexity.

A third process air conditioning system is depicted in Figure 6. This system utilizes a turbo compressor (could be either simple cycle or boost strap cycle) and ram air heat exchangers to compress and cool the process air. Good performance is achieved at the expense of higher bleed air consumptions.

The system of choice is dependent on the aircraft and mission characteristics. Some helicopters lack an ECS and would favor the first system. On the other hand, flight at supersonic speeds negates the use of ram air as a coolant and indicates the inerting system should be carefully integrated with the ECS.

2.5 Design Considerations And Trade-Offs

The design process begins with an assessment of the inert gas flow rate requirements throughout the mission. Aircraft characteristics that influence the inerting requirements are:

- o Fuel-tank volume;
- o Fuel/ullage temperature histories;
- o Fuel burn rate;
- o Climb/descent rates; and
- o Fuel tank overpressure/underpressure limitations.

Additional features and ground rules that influence inerting requirements are:

- o Initial fuel state (e.g., air saturated at sea level);

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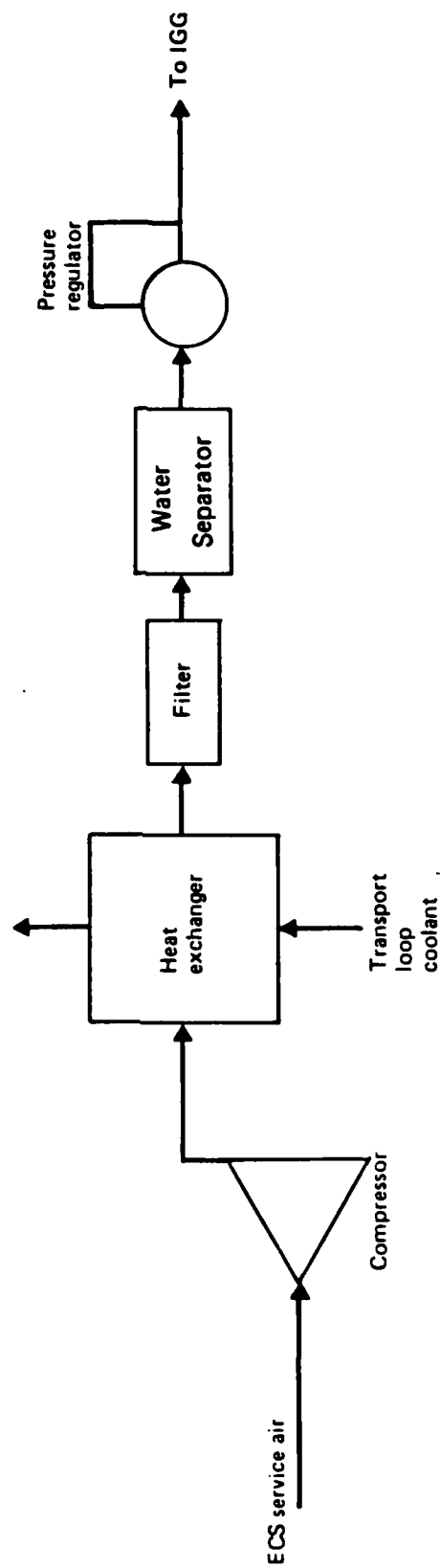
Figure 5. Supply Air Conditioning Using the ECS System

ECS service air

Compressor

Heat exchanger

Transport loop coolant

Filter

Water Separator

Pressure regulator

To IGG

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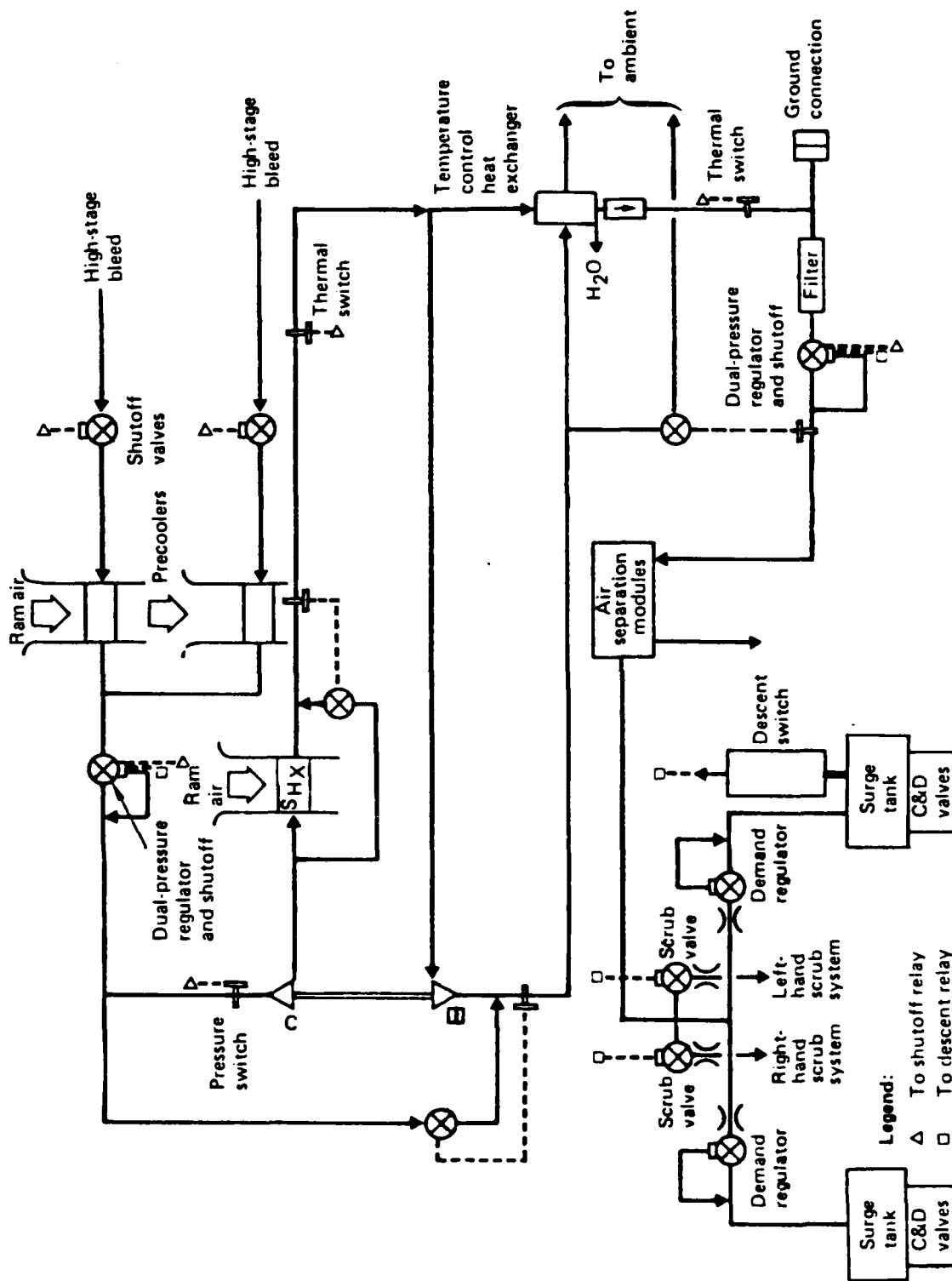
Figure 6. Supply Air Conditioning Using a Turbo Compressor

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o Requirement for emergency descent; and

o Ullage oxygen concentration ($\leq$9% for entire mission - or >9% during brief flight segments).

The inert gas flow and quality requirements allow the OBIGGS to be sized. The inert gas requirements on aircraft such as helicopter or transport category with relatively low descent rates may be satisfied directly by the OBIGGS, eliminating the need for a stored gas system. The OBIGGS capacity can then be determined from either a climb scrub requirement when gas quality is more important or descent repressurization where flow rate is more important.

For higher performance aircraft with high descent rates it may be impractical to size the inert gas generation for the flow rates required for descent repressurization. In this case a high pressure gas storage system could be employed. The trade between inert gas generation capacity and storage system capacity generally favors the smallest inert gas generator consistent with time requirements for charging the high pressure bottles. The problem with the gas storage concept is the relatively low reliability of current high pressure gas compressors.

2.6   Control System

Since the oxygen concentration increases with inert gas flow rate in an OBIGGS, one could theoretically develop a control system which would optimize the OBIGGS inert gas production for each part of the mission. Moderate flow rates would be used for fuel scrubbing, low flow rates for cruise, and high flow rates for descent. A control system optimized for each phase of flight would be highly complex and more likely to have reliability problems. The other extreme would be a control system which controls the OBIGGS output to a single operating point (inert gas flow rate and oxygen concentration). The latter would make inefficient use of the inert gas but should minimize maintenance and reliability problems. The appropriate control system also depends on whether a stored gas or a demand system is used.

Although the stored gas system has the complexity of a compressor and storage bottles, the control system can be quite simple since the compressor in a

stored gas system operates most efficiently with a constant production rate of inert gas. The discharge rate from the storage tanks can be controlled by conventional pressure regulators.

The flow rate in a demand system can be controlled with a regulated valve or choked flow orifices. The regulated valve offers considerable flexibility at the expense of the need to continually monitor and adjust the outflow rate. The choked flow orifices automatically control the inert gas flow rate but impose practical limits on the number of different rates that can be utilized.

3.0 DEVELOPMENT OF C-5B OBIGGS DESIGN

Currently the C-5A and C-5B airplanes are designed with a liquid nitrogen (LN_2) storage system which enhances airplane fire safety and survivability by inerting the fuel tanks and providing fire protection for a number of airplane bays or compartments. Fuel tank inerting is achieved by metering LN_2 from a central storage location to maintain inert fuel tank ullage volumes. Compartment fire protection is provided by flowing gaseous nitrogen to the affected compartment at a rate which suppresses the fire but does not overpressurize the compartment.

A study of the feasibility of using NEA for fuel tank inerting and compartment fire suppression on the C-5A airplane (Ref. 6) revealed that:

o NEA inerting/fire suppression systems are comparable to LN_2 systems on the basis of weight and protection afforded, but the NEA systems would have lower life cycle costs.

o The primary disadvantage of the NEA system is its larger volume compared to the LN_2 system; to minimize the volume penalty, it was more practical to provide high NEA demands from a gas storage system than to size the air separation modules for the peak demand flow.

o NEA offers multiple shot engine fire protection compared with the two shots offered by the Halon system.

One objective of the current study was to develop a preliminary design of an OBIGGS for the C-5B airplane. This study was similar to the Ref. 6 study but had some significant differences. The ground rules for the current study were:

o The design mission profiles and fuel system pressurization schedules used for sizing the C-5A system were valid for C-5B system sizing.

o The OBBIGS design was required to provide full time fuel tank inerting except that the dive valve could open during an emergency descent if the maximum ullage oxygen concentration did not exceed 12% by volume. (Studies have shown that the OBIGGS size and weight can be significantly reduced if the dive valve is allowed to open during an emergency descent to allow ambient air to assist in the tank repressurization process. The current LN_2 system on the C-5 airplanes is designed to limit the oxygen concentration to a maximum of 9% under all conditions. Therefore, the OBIGGS design in this study carries with it a degree of risk in an emergency descent which the LN_2 system does not have. Note also that the OBIGGS design for C-17 airplane does incorporate a 9% oxygen limit for all operating conditions.)

o The OBIGGS design was optimized for fuel tank inerting. However, once the design was established, the use of the OBIGGS to provide NEA for compartment fire protection was evaluated.

o The OBIGGS design was developed for a stored gas system rather than a demand system, based on the results of the C-5A study.

3.1 Existing C-5B Fire Protection System

The C-5B is a well protected military airplane in terms of fire prevention and suppression. A liquid nitrogen (LN_2) system provides the airplane with both fuel tank inerting and fire protection for wing dry bays and small fuselage compartments. The engines, auxiliary power units, and large fuselage compartments are protected by Halon fire extinguishing agents. The protection offered by these systems is reviewed in this section, since present systems provide the baseline against which to compare the OBIGGS fuel tank inerting design.

It was assumed that the C-5B inerting system was the same as the C-5A system as described in Ref. 6.

3.1.1 Fuel Tank Inerting System

The fuel tank inerting system provides sufficient inert gas to maintain an inert ullage ($\leq$ 9% oxygen concentration) at all times. Two subsystems are required for the inerting system: one for fuel scrubbing and the second to maintain an inert ullage during cruise and descent.

The C-5B LN_2 dewars (1500 pounds capacity) are capable of maintaining an inert ullage during two maximum range, maximum altitude sorties (one round trip), separated by a 48 hour period of ground standby without servicing. The LN_2 remaining at the end of the design missions is the minimum reserve for fire suppression; the entire LN_2 supply at earlier mission times is available for fire suppression. The one-way design mission profile is shown in Figure 7; the time enroute is on the order of 8 hours.

3.1.1.1 Fuel Scrub Subsystem

Fuel is scrubbed on the C-5B airplane using the separator-aspiscrubber technique, which is shown schematically in Figure 8. This technique relies on a pressure fueling system to provide the motive force for the incoming fuel. The low pressure created by fuel flowing through the aspirator draws in ullage gases and dissolved oxygen is scrubbed from the fuel during the subsequent mixing process. The ullage gases in an LN_2 inerting system are well-suited for scrubbing because they have a high nitrogen concentration due to fuel tank repressurization from the previous flight. The fuel and gases then undergo a separation process; the scrubbed fuel flows to the bottom of the tank and the resultant oxygen enriched gases flow out the top of the separator to be vented overboard.

3.1.1.2 Fuel Tank Pressurization Subsystem

Fuel tank repressurization with inert gas prevents atmospheric air from entering the fuel tanks as fuel is consumed or during descent. The repressurization subsystem is incorporated into the fuel tank vent system and maintains a slight positive gauge pressure in the tank both on the ground and throughout flight. Tank pressure is normally controlled automatically by a system of pressure regulators and valves. Secondary components are available as backups if the primary units fail.

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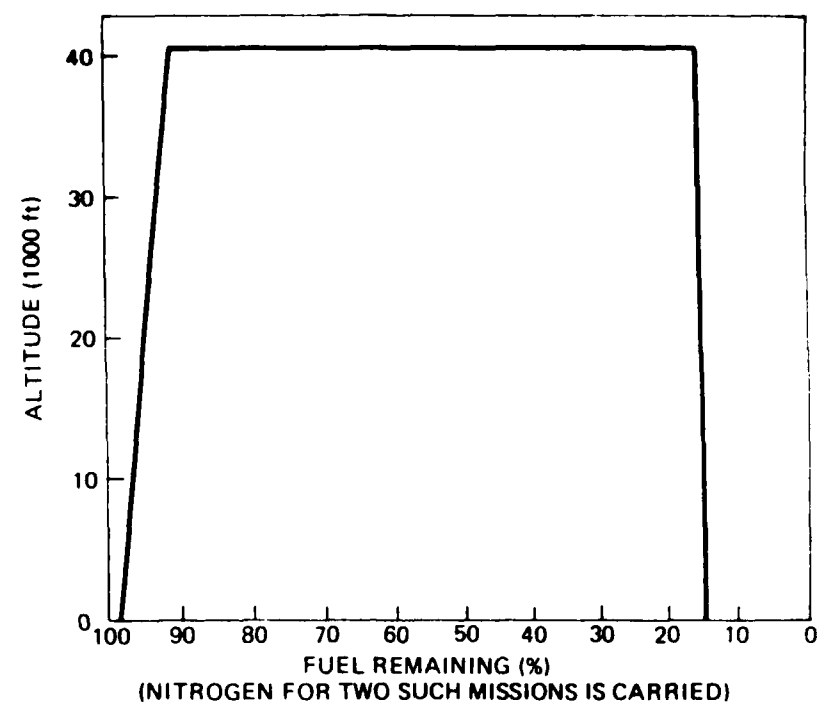
Figure 7. Maximum Range Mission Profile
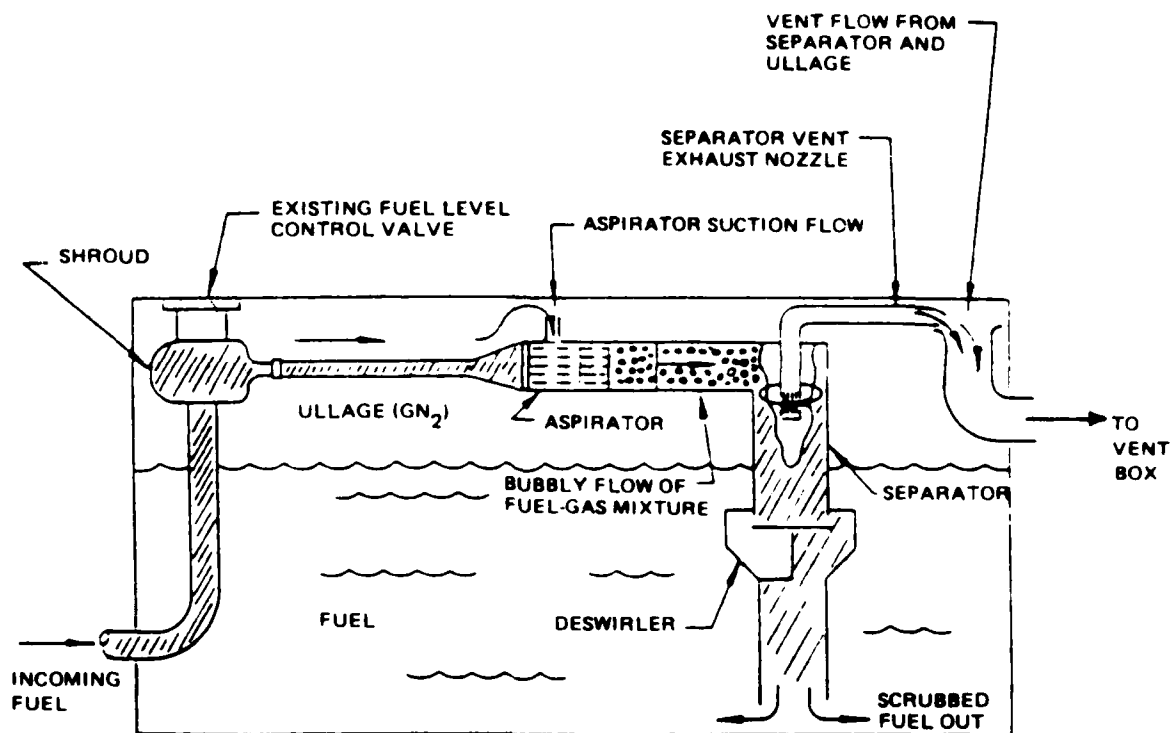
Figure 8. Schematic, Separator Aspiscrubbing

The means of controlling fuel tank pressure are diagrammed in Figure 9, and described as follows:

o   the pressure regulator admits nitrogen on demand by sensing the difference between ambient and vent box (fuel tank) pressures;

o   the climb valve vents ullage gas to prevent differential pressures in the fuel tanks which could cause structural damage; and

o   the dive valve admits air into the fuel tank vent system to prevent structural damage in the event the flow rate of repressurization inert gas is not adequate. In normal operation, the regulators supply a sufficient quantity of inert gas and the dive valves do not open.

Figure 10 provides an overview of the C-5B pressurization system installation. LN_2 flow is regulated at its dewar source, transferred to the outboard main fuel tanks as a liquid, and vaporized in heat exchangers just prior to entering the fuel tank vent box. A detailed schematic of the system and its components is shown in Figure 11.

During cruise, a small flow of inertant is sufficient to maintain tank pressure as fuel is consumed. The greatest demand on the repressurization system is during descent, when ambient pressure is increasing rapidly, and a large flow of nitrogen is needed to maintain positive tank pressure. In Figure 12, the predicted pressure differential for a descent from 40,000 feet with normal primary regulator operation in each fuel tank is shown as a function of altitude.

3.1.2 Fire Suppression Systems (FSS)

Twelve zones on the aircraft are afforded fire protection by the LN_2 system, while eight others are protected by Halon 1301 or Halon 1202. In general, the fire suppression system specification requires that:

o   When LN_2 is used in a zone, the quantity discharged be sufficient to reduce the oxygen concentration in the zone to 10% or less within 10 seconds, without exceeding allowable compartment overpressures.
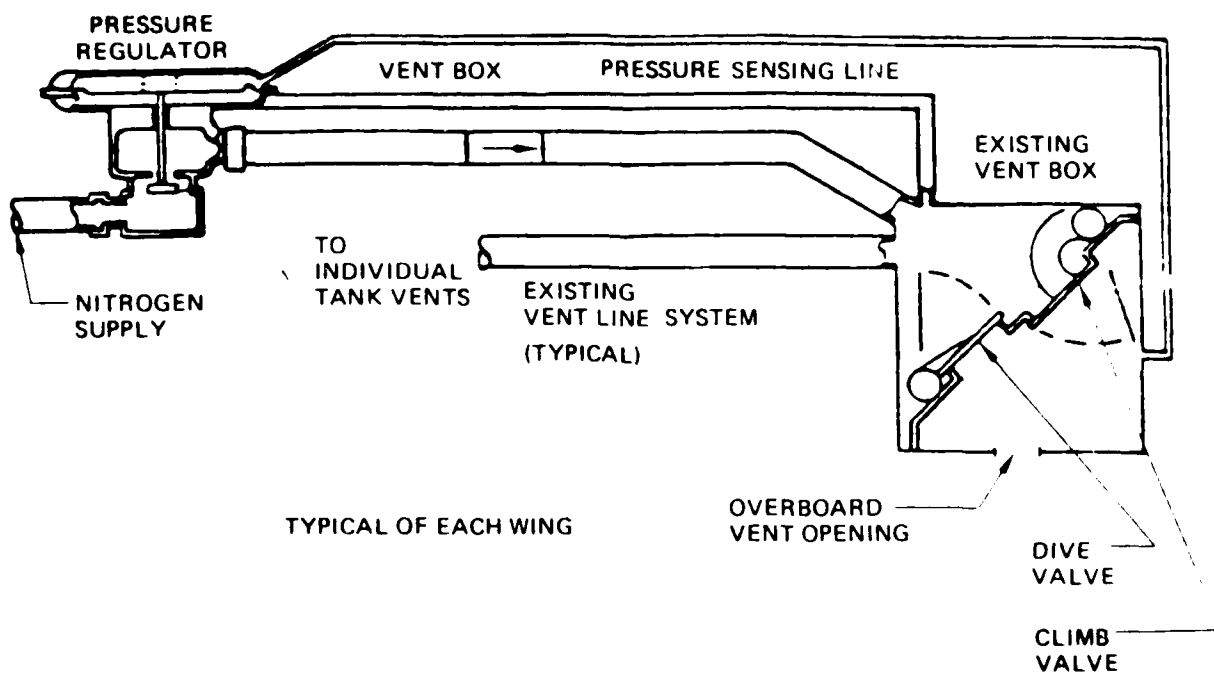
Figure 9. Flow Diagram—LN$_2$ Pressurization Subsystem
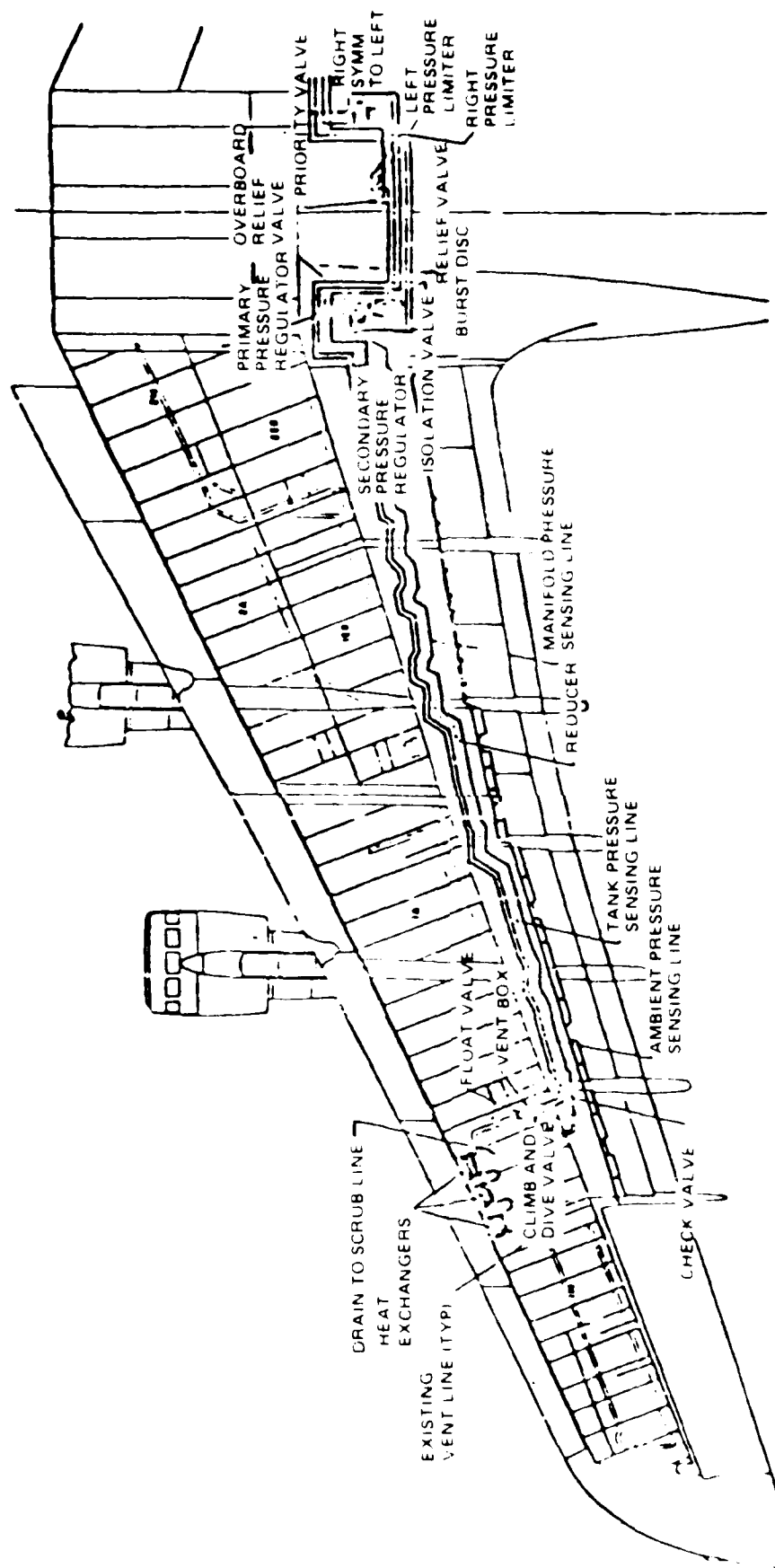
Figure 10. Pressurization Installation Schematic
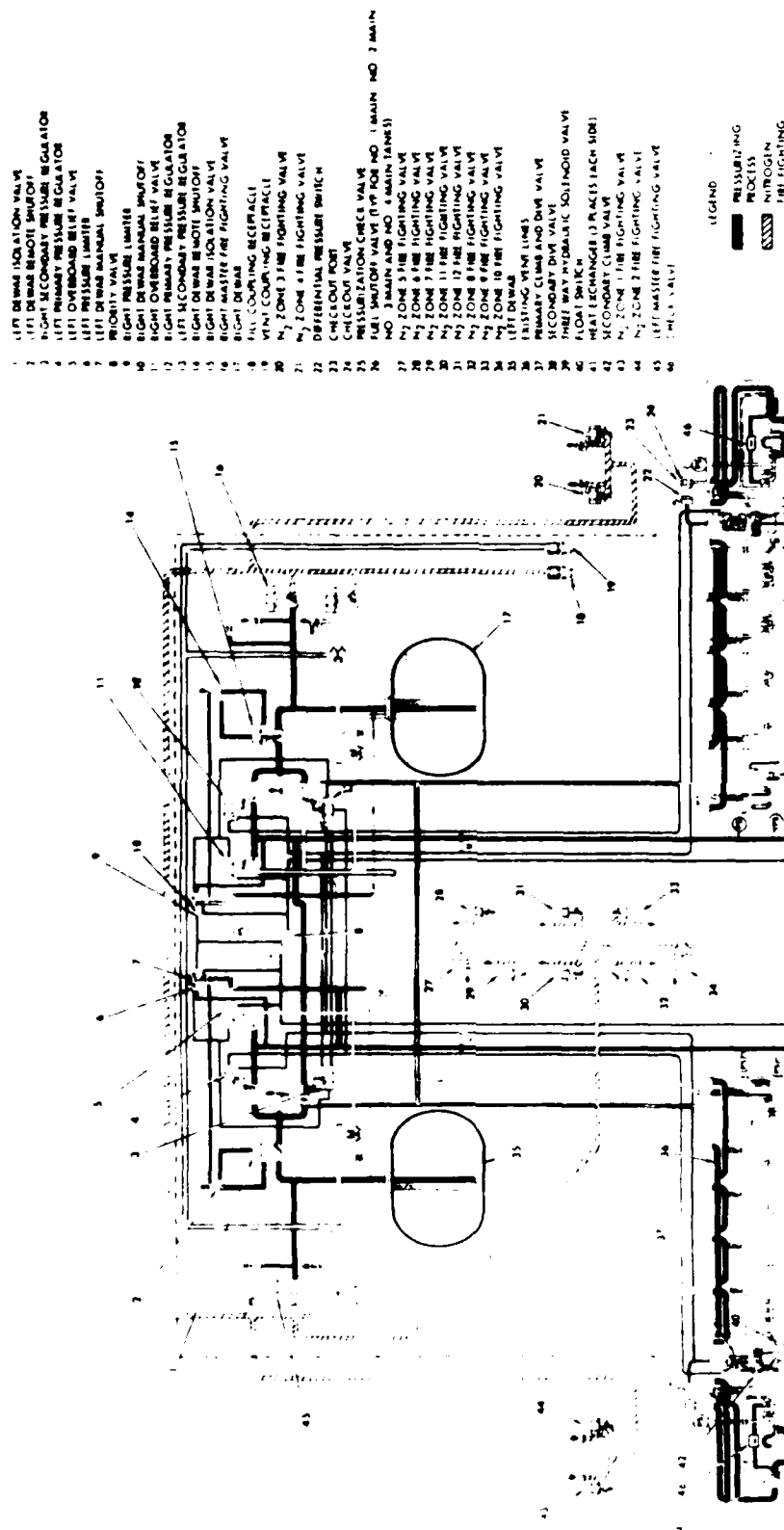
Figure 11. Nitrogen Fire Fighting and Pressurizing Process Functional System Diagram
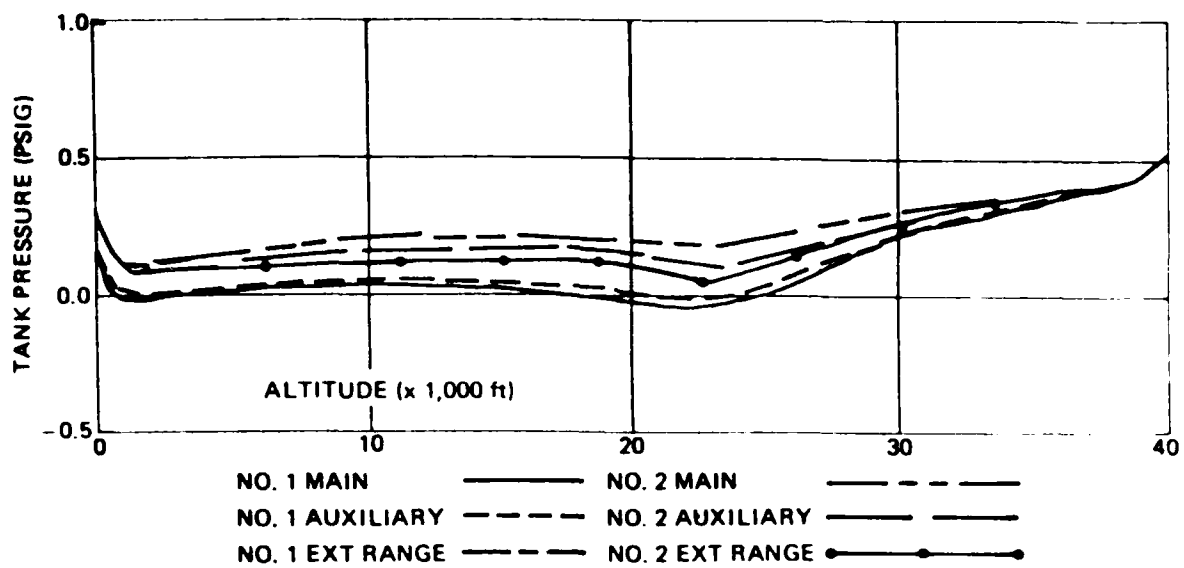
Figure 12. Descent With Normal Regulator Operation

o When Halon is used, the agent be completely discharged within 5 seconds, and its volumetric concentration must exceed 6% within 4 seconds.

3.1.2.1 Liquid Nitrogen System

The 12 aircraft zones protected by LN_2 are indicated in Figure 13. Two dewars located in the wing roots are used to store the nitrogen used for both inerting and fire fighting. The LN_2 quantity provides a reserve of nitrogen for fire fighting over and above the amount required for inerting during the two specified maximum length missions; the minimum fire suppression reserve is 458 pounds in the aspiscrub subsystem (Figures 14 and 15).

Figure 11 diagrams the LN_2 fire suppression system as well as the fuel tank inerting pressurization system, and shows the relative positions of the master fire fighting valves and individual zone fire fighting valves. Figures 16 and 17 show a three-dimensional view of the valves and the LN_2 dewars as they are located on the aircraft. When the fire extinguishant discharge switch is pressed, the following events occur:

o both master fire fighting shutoff valves open and the nitrogen line is pressurized to 19 (±1) psig; and

o the zone valve for the zone selected opens, and LN_2 is discharged into the zone.

The amount of LN_2 discharged is determined by a flow timer in the fire suppression/inerting system central processing unit.

The quantities of LN_2 discharged into the various protected zones (Ref. 6) are listed in Table 1, as are the compartment volumes and approximate discharge times. In effect, fire extinguishment is designed to be accomplished by replacing each pound of air in a zone with 1 pound of nitrogen (Figure 18). Given the amount of mixing that occurs during injection, this procedure is designed to reduce the oxygen content to less than 9%.
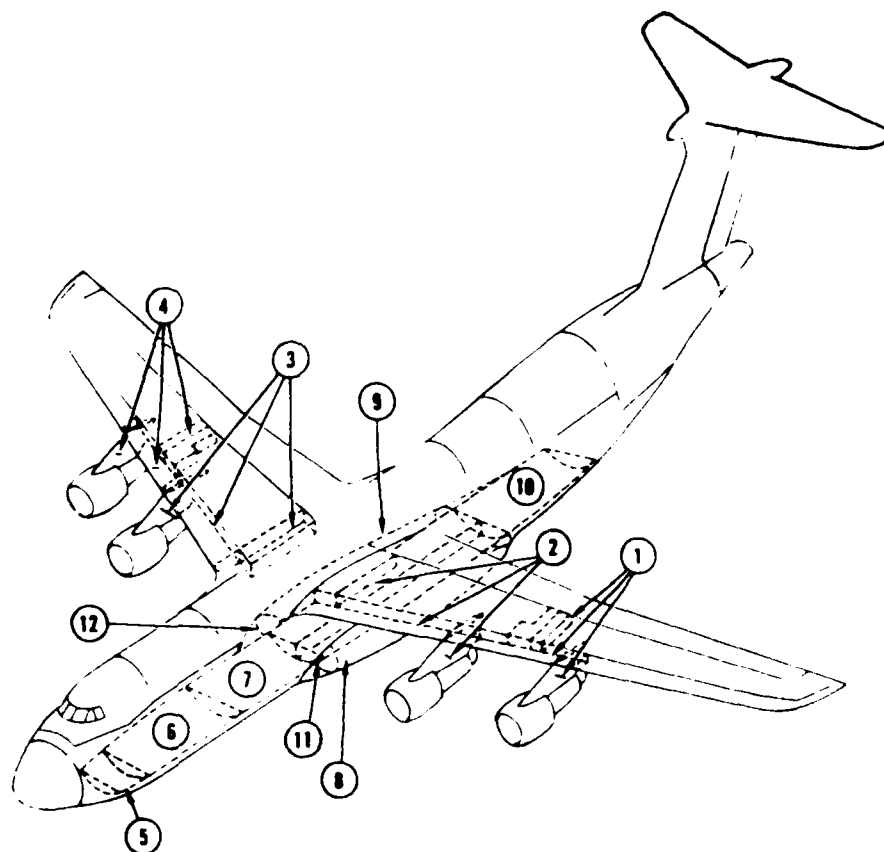
ZONE	SPACES INCLUDED IN ZONE
①	LEFT WING DRY BAY, LEFT OUTBOARD LEADING EDGE, LEFT OUTBOARD PYLON LEADING EDGE
②	LEFT WING ROOT DRY BAY, LEFT INBOARD LEADING EDGE, LEFT INBOARD PYLON LEADING EDGE
③	RIGHT WING ROOT DRY BAY, RIGHT INBOARD LEADING EDGE, RIGHT INBOARD PYLON LEADING EDGE
④	RIGHT WING DRY BAY, RIGHT OUTBOARD LEADING EDGE, RIGHT OUTBOARD PYLON LEADING EDGE
⑤	NOSE WHEEL WELL
⑥	CARGO UNDERFLOOR, FORWARD
⑦	CARGO UNDERFLOOR, MID
⑧	LEFT MAIN WHEEL WELL
⑨	RIGHT MAIN WHEEL WELL
⑩	CARGO UNDERFLOOR, AFT
⑪	LEFT PTU COMPARTMENT
⑫	RIGHT PTU COMPARTMENT

Figure 13. LN_2 Fire Suppression System Fire Zones

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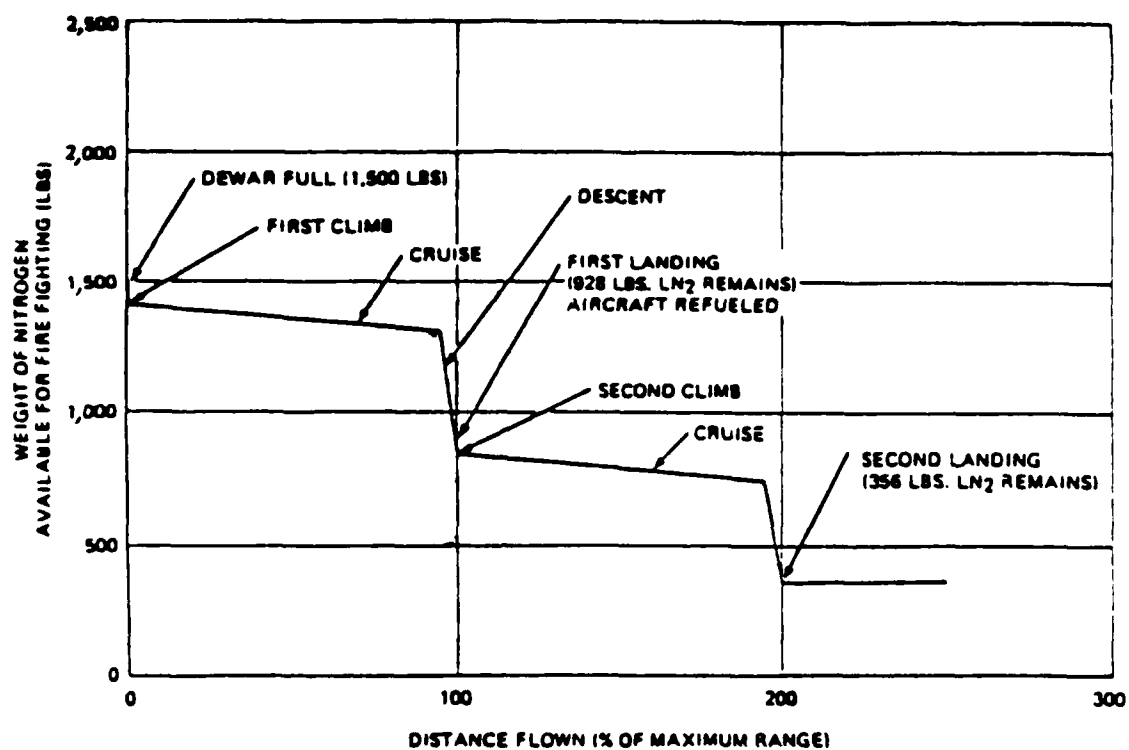
Figure 14. LN_2 Quantity vs. Distance Flown C-5B With the Climb Scrub Subsystem
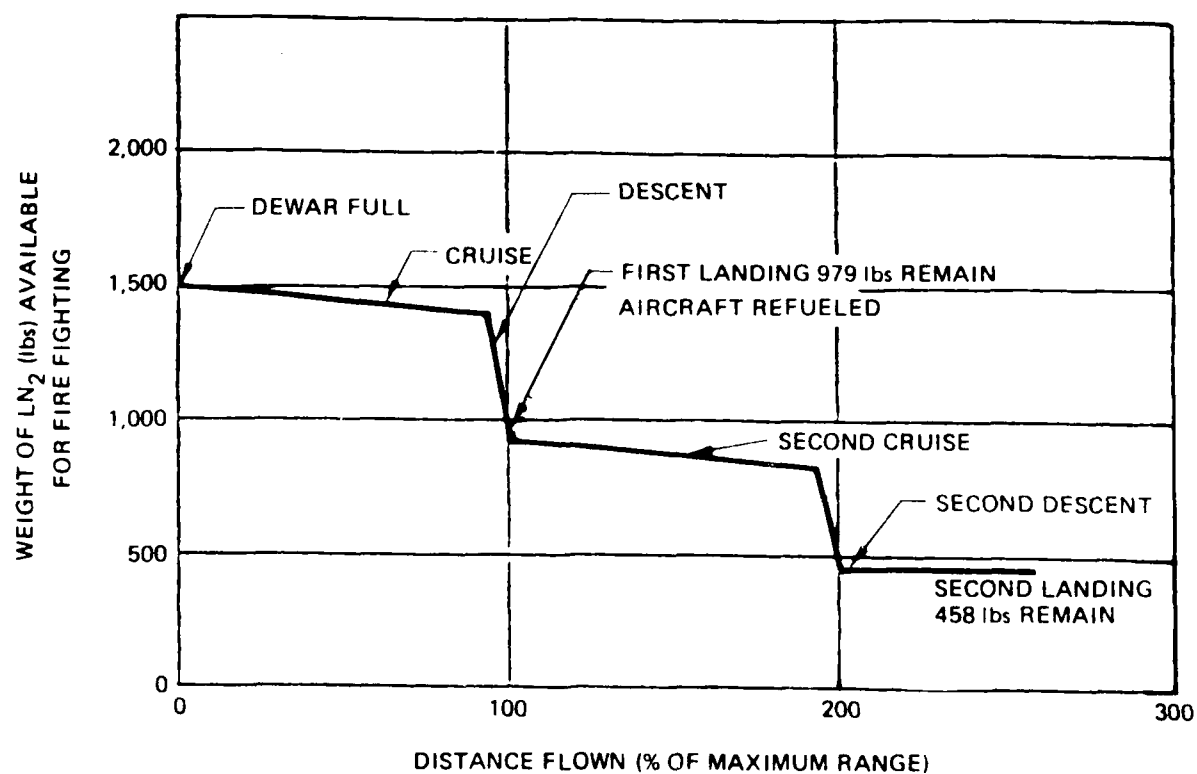
Figure 15. *LN$_2$ Quantity vs. Distance Flown C-5B With the Separator Aspiscrub Subsystem*

Figure 16. LN_2 Fire Suppression System Valve Locations

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MASTER FIRE
SHUTOFF VALVE

PRESSURE
SWITCH
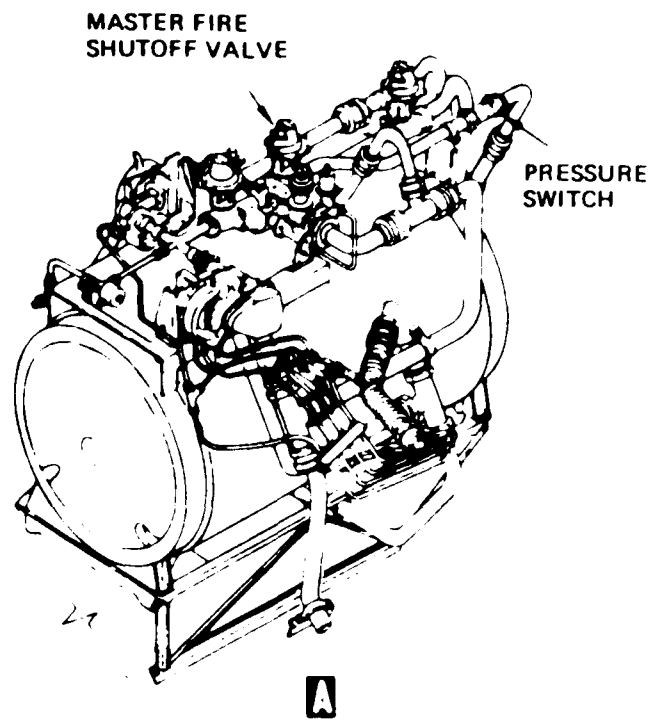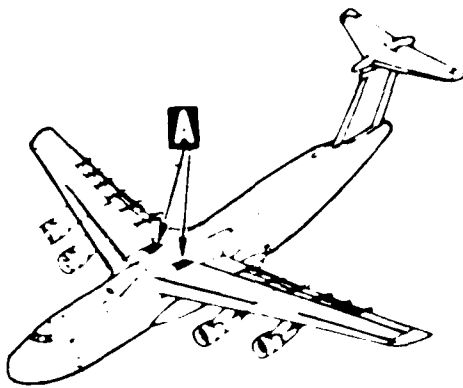
Figure 17.   LN₂ Dewar Locations

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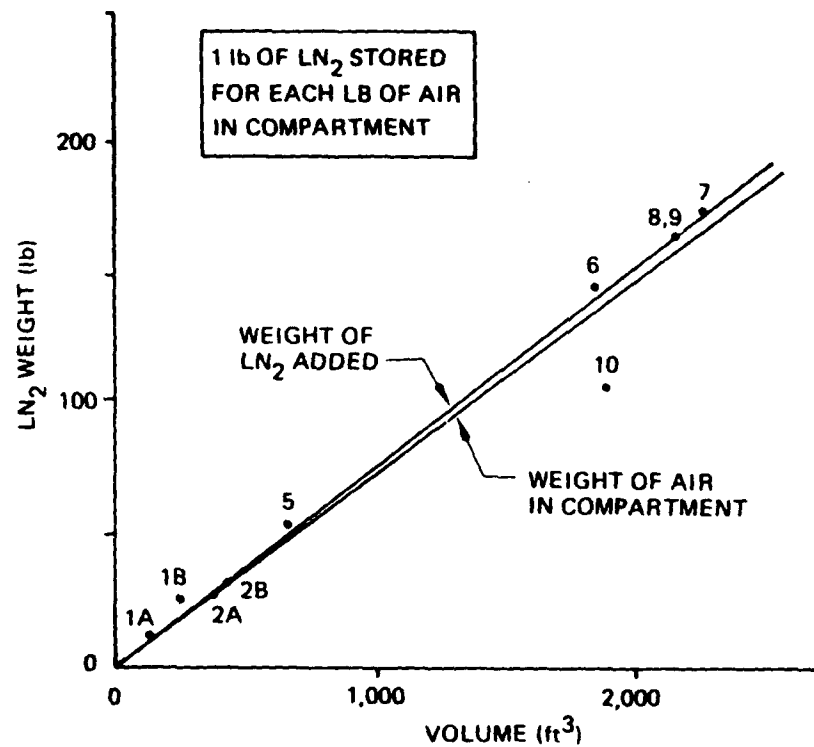
Figure 18. *LN₂ Delivered by Current System to Each Zone*

Table 1. LN_2 Fire Suppression System

PROTECTED ZONE	ZONE VOLUME (FT^3)	QUANTITY OF LN_2 DELIVERED (LB)	DISCHARGE TIME (SEC)
1 LEFT OUTBOARD WING			41-52
A OUTBOARD LEADING EDGE	114.0	11.7	
PYLON LEADING EDGE	4.0	2.0	
B OUTBOARD DRY BAY	138.6		
INBOARD DRY BAY	46.2	26.2	
AFT DRY BAY	46.2		
	349.0	39.9	
2 LEFT INBOARD WING			41-52
A OUTBOARD LEADING EDGE	228.0	30.2	
INBOARD LEADING EDGE	228.0		
PYLON LEADING EDGE	4.0	1.6	
B WING ROOT DRY BAY	374.0	25.9	
	834.0	57.7	
3 RIGHT INBOARD WING	SAME AS 2		
4 RIGHT OUTBOARD WING	SAME AS 1		
5 NOSE WHEEL WELL	640	53	36-47
6 FWD. UNDERFLOOR CARGO COMPARTMENT	1809	146	36-47
7 CENTER UNDERFLOOR CARGO COMPARTMENT	2243	174	41-52
8 LEFT MAIN WHEEL WELL	2140	165	36-47
9 RIGHT MAIN WHEEL WELL	2140	165	36-47
10 AFT UNDERFLOOR CARGO COMPARTMENT	1873	107	36-47
11 LEFT POWER TRANSFER UNIT (PTU)	313	49	41-52
12 RIGHT PTU	313	49	41-52

No heat exchanger is provided to vaporize the LN_2 prior to its discharge into the affected zone. A direct relationship exists between flame temperature and fire stability, thus the cooler the entering nitrogen, the better its fire extinguishing capability. Any nitrogen trapped in the lines after the zone valve closes flows back into the dewars through the master fire and fill valves. A small hole in one of the tees (left hand dewar) allows bleed off of the residual nitrogen in 5 to 10 minutes.

3.1.2.2 Halon Fire Suppression System

Zones protected by Halon (Figures 19 and 20) are described by number in Table 2 (Ref. 6). The Halon containers and locations in Zones 13 through 17 were chosen in an effort to maximize agent dispersion. The system is required to attain a volume concentration of 6% (at sea level and 70°F) or greater within 4 seconds and maintain a concentration of at least 6% for 5 minutes with the circulating fans off.

Toxicity is a concern when Halon-type agents are used in areas inhabited by personnel; thus, control of agent concentration is provided. The number of Halon 1301 bottles discharged into Zones 13, 14, and 15 can be varied manually, depending on the size of the cargo load (see footnote of Table 2) to keep the concentration by volume below 10%.

Three identical Halon 1202 subsystems are installed which protect Zones 18, 19, and 20. The engine/pylon Halon 1202 extinguishing systems each serve two engines, providing two discharges to one nacelle, or one discharge to both nacelles. Agent is directed into the engine compartments at the upper forward section of the engine which encloses the high pressure compressor and the upper aft section which encloses the turbine. The intent is that the agent envelops the engine by flowing down and around both sides of the engine.

The APUs are located in the lower aft corner of the right main wheel well, and are protected by a bottle capable of providing one discharge into each of the two APU compartments, or two discharges into one compartment.
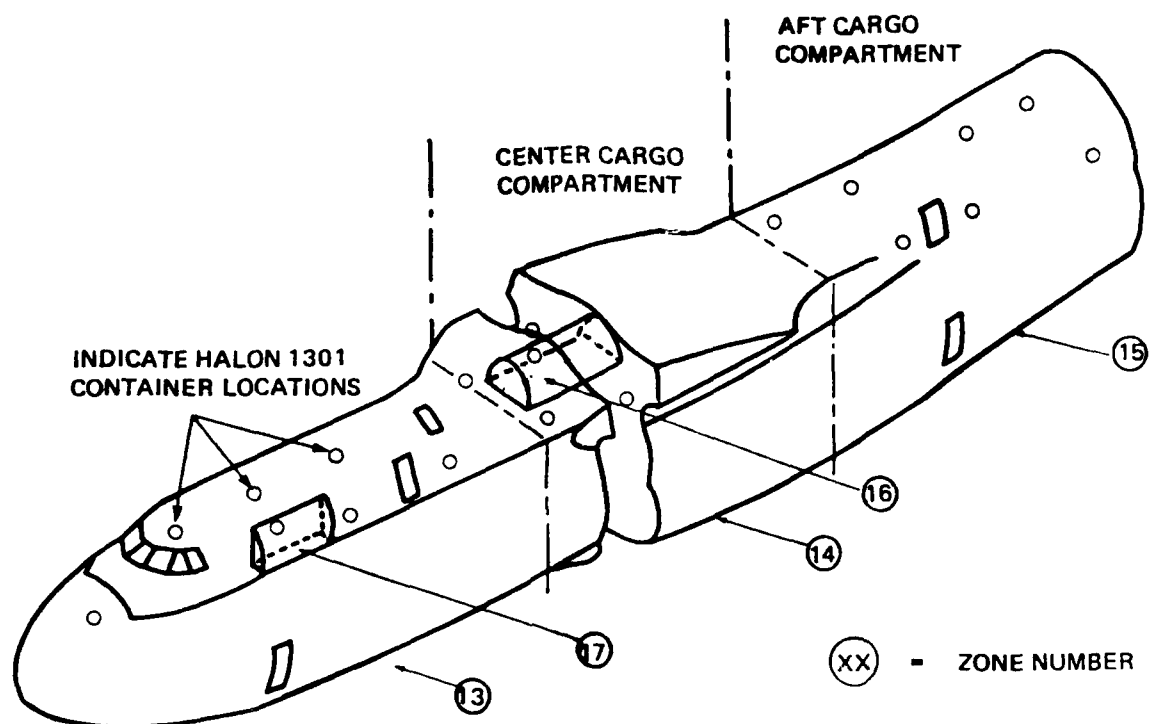
Figure 19. C-5B Zones Protected by the Halon 1301 Fire Supression System

⑬ FORWARD CARGO COMPARTMENT

⑭ CENTER CARGO COMPARTMENT

⑮ AFT CARGO COMPARTMENT

⑯ CENTER WING

⑰ AVIONICS
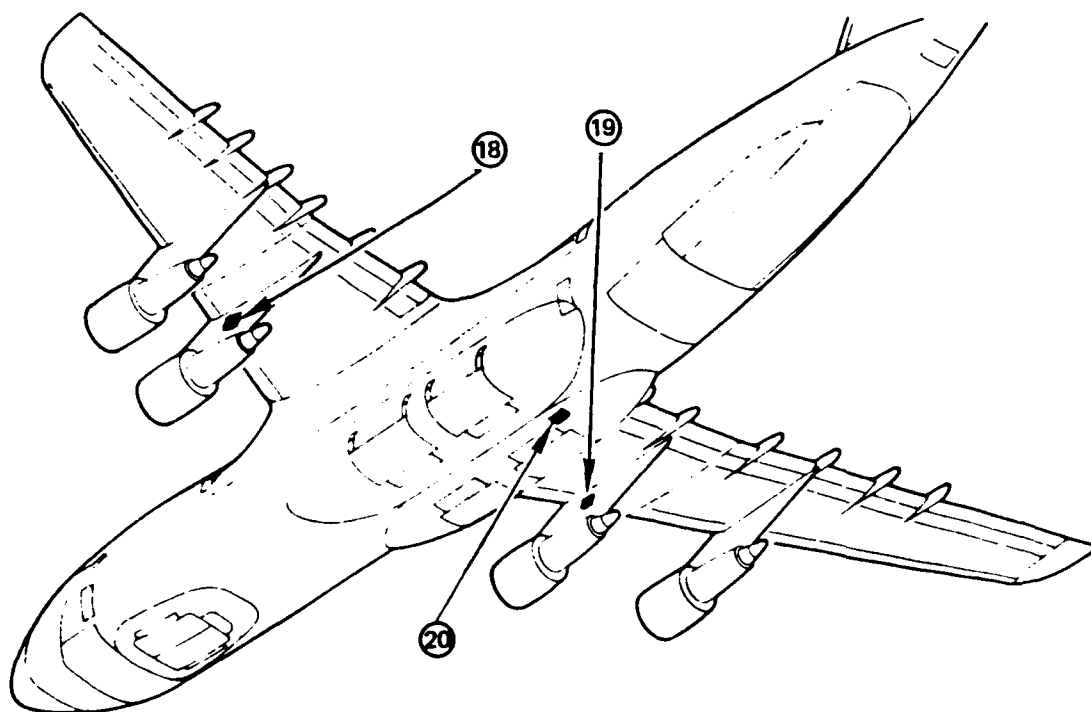
Figure 20. C-5B Zones Protected by the Halon 1202 Fire Suppression System

⑱	ENGINE NACELLE LEFT
⑲	ENGINE NACELLE RIGHT
⑳	AUXILIARY POWER UNIT (APU)

Table 2. Halon Fire Suppression System

	PROTECTED ZONE	ZONE VOLUME (FT^3)	HALON TYPE	QUANTITY STORED	WEIGHT INCLUDING CYLINDER (LB)
13	FWD CARGO COMPARTMENT		1301	6-70 LB BOTTLES	566
14	CENTER CARGO COMPARTMENT	46,651 ft^3 TOTAL*	1301	4-70 LB BOTTLES	377
15	AFT CARGO COMPARTMENT		1301	7-70 LB BOTTLES	660
16	CENTER WING	2760.0	1301	2-70 LB BOTTLES	204
17	AVIONICS	300.0	1301	10 LB	18
18	ENGINE NACELLE LEFT	139.0	1202	2-7.5 LB BOTTLES	27.5
19	ENGINE NACELLE RIGHT	139.0	1202	2-7.5 LB BOTTLES	27.5
20	AUXILIARY POWER UNIT (APU)	UNK.	1202	2-4.5 LB BOTTLES	18
					1898.0

* NUMBER OF BOTTLES DISCHARGED DEPENDS ON CARGO VOLUME:

CARGO VOLUME	NO. OF BOTTLES DISCHARGED
UNDER 10,000 FT^3	ALL 17 BOTTLES DISCHARGED
10,000 - 20,000 FT^3	13 BOTTLES DISCHARGED
OVER 20,000 FT^3	9 BOTTLES DISCHARGED

3.1.3 Summary of Existing C-5B Inerting and Fire Suppression System Size

The weight and volume, as well as the performance, of the LN_2/Halon inerting and fire suppression systems needed for comparison with the conceptual NEA/Halon systems, are summarized below:

	WEIGHT (LB)
LN_2 dewars (including 1500 LBS of LN_2)	2713 total
Installation assuming climb scrub system (lines, wiring, supports, fittings, and heat exchangers)	1059
Halon bottles (including 1379 LB of Halon 1202 and 1301)	1898
Total	5670

The total volume occupied by the LN_2/Halon inerting and fire suppression systems is about 40 cubic feet.

3.2 C-5B Inert Gas Requirements for Fuel Tank Inerting

The airplane mission profile describes the altitude, Mach number, and engine power settings inflight as a function of time. From this, the fuel tank inerting requirements and the mass flow of engine bleed air required by the inert gas generator can be calculated.

The LN_2 fuel tank inerting system design mission is a maximum altitude, maximum range mission, involving cruise at 40,000-feet, and a rapid descent from 40,000 feet at the end of the mission (Figure 21a). The actual profile, which features several step climbs, was simplified for analysis as shown in the figure. The simplified profile reduces the number of mission conditions and substitutes the more demanding, 40,000-feet cruise altitude. The climb and descent rates associated with the simplified profile are shown in Figure 21b.

To be comparable with the LN_2 inerting system, the OBIGGS was designed to perform both fuel scrubbing and fuel tank pressurization while maintaining full time inerting (< 9% oxygen by volume) except for emergency descent (see ground rules in Section 3.0). Each mission segment was examined for NEA requirements, and the maximum demands were used for sizing system components.

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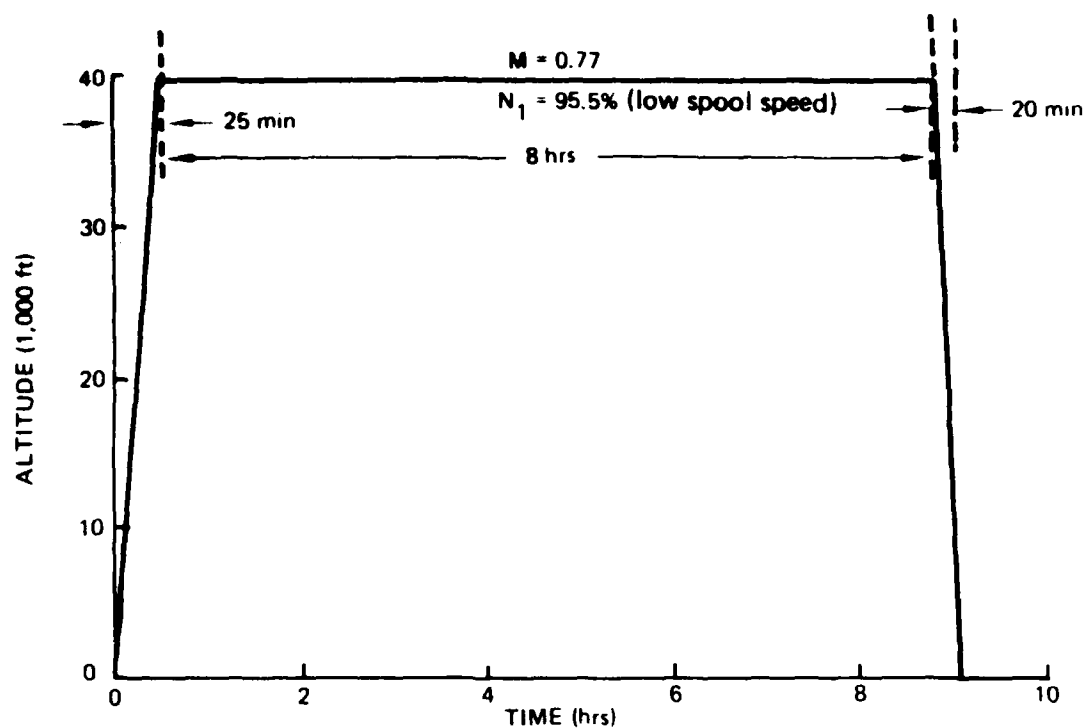
Figure 21a. C-5B Standard Mission Profile
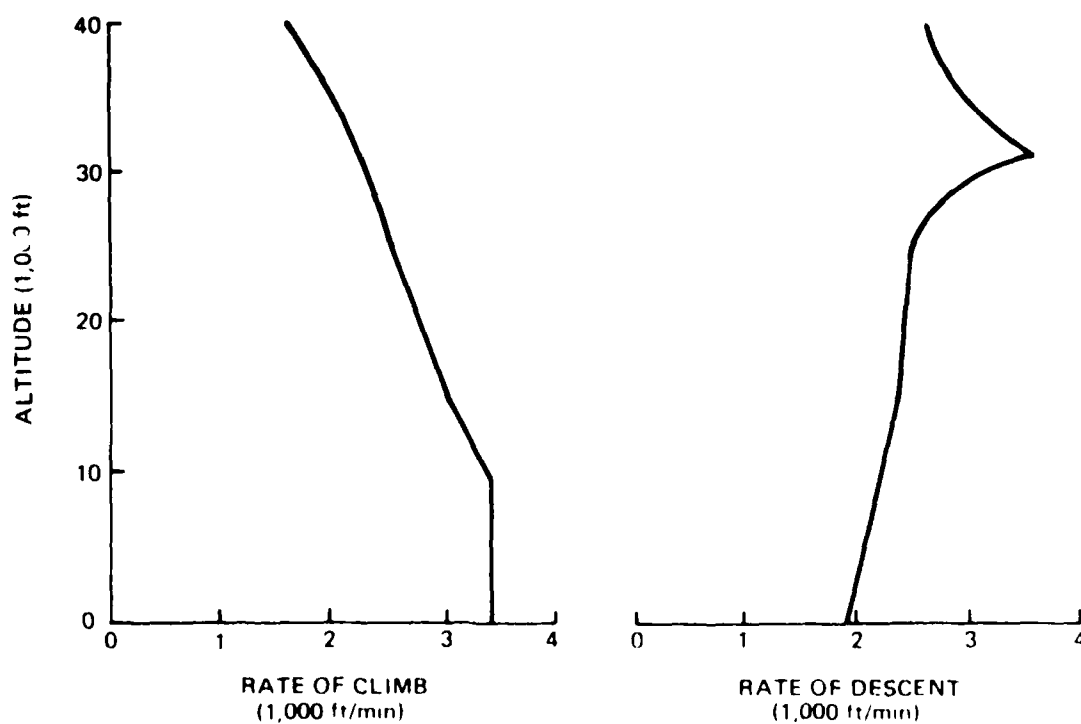
Figure 21b. Climb and Descent Rates

3.2.1 NEA Requirements for Airplane Climb

The C-5A NEA study (Ref. 6) revealed that aspiscrubbing alone was not practical with NEA; combining aspiscrubbing with ullage washing or the climb scrubbing technique would be required. Since aspiscrubbing is standard on the C-5B airplane with the LN_2 system, either ullage washing by flowing NEA through the vent system or replacing the aspiscrubbing units with scrub nozzles would be required with an OBIGGS. NEA requirements for both concepts are discussed below.

Calculations of the effect of scrub flow on ullage oxygen concentration are tractable if the dissolved gases in the fuel are in equilibrium with the ullage gases (have the same partial pressures). Fortunately, the equilibrium assumption has been shown to provide excellent agreement between calculations and test data (see Volume III, Parts 1 and 2). Evidently, the mixing of inert gas and fuel during scrubbing and the dynamics in the airplane (slosh, vibration and pumping) are sufficient to maintain near equilibrium conditions. The fuel scrubbing computer code assumes the approach discussed in Section 2.3.1 and the following sequence of events during a compute interval (see Figure 22):

o a mass of scrub gas is injected into the fuel;

o the scrub gases mix with initial dissolved gases to form a new equilibrium composition of dissolved gases;

o gases at the new composition evolve into the ullage and mix uniformly with the initial ullage gases; and

o gases at the new ullage gas composition are vented until the ullage pressure boundary condition is satisfied.

The fuel and ullage conditions at the end of the time step become the initial conditions for the next time step. The fuel consumed during the time increment is accounted for by adjusting the ullage volume and fuel volume during each time step. Details of the analysis are reported in Ref. 6.
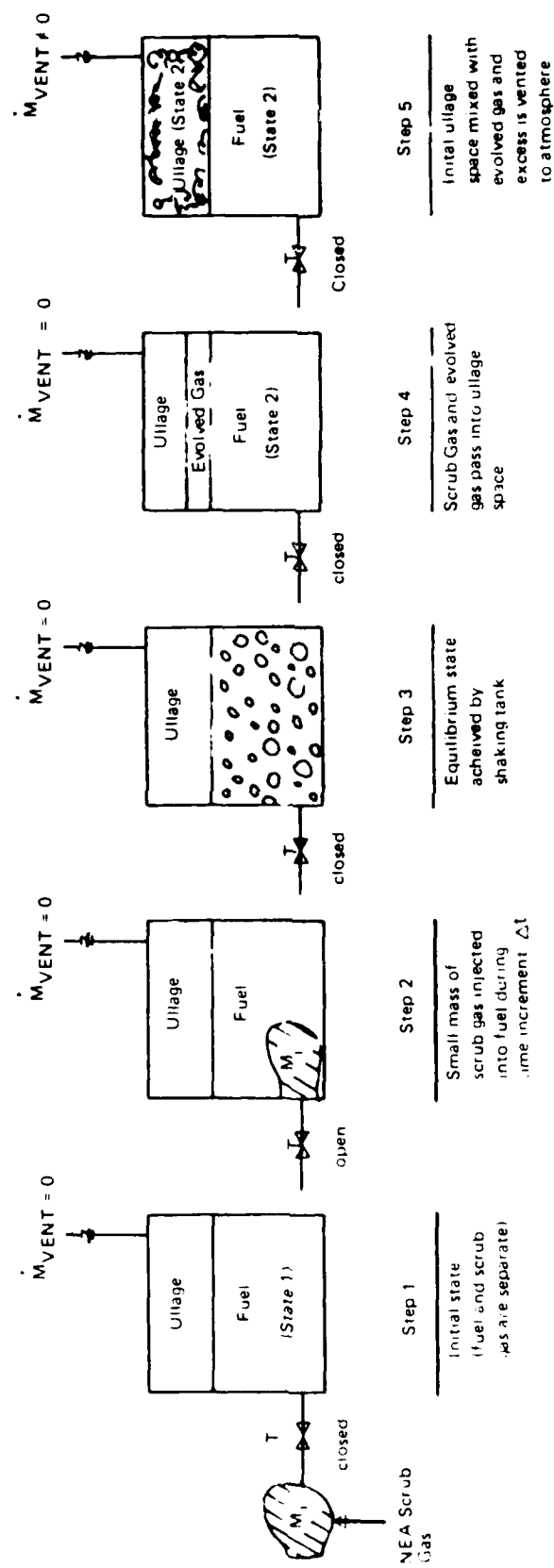
Figure 22. Scrubbing Process Used in Analysis

3.2.1.1 Climb Scrubbing Analysis

The climb scrub concept requires inert gas to flow during airplane climb out through a network of scrub nozzles located in the bottom of the fuel tanks. The nozzles disperse the incoming NEA into a very large number of tiny bubbles. Bubbles rich in nitrogen will displace dissolved oxygen from the fuel during their excursion from the bottom of the tank to the surface, with an efficiency depending on the number, size, and distribution of the bubbles. The main advantage of the climb scrub nozzle concept over the aspiscrub concept is that lower NEA qualities (higher oxygen fraction) can be used to scrub the fuel (Ref. 6). Since NEA quality and production rate are inversely related, a trade-off between quality and quantity was made. This inverse relationship is illustrated by the following example: prototype IGG units recently tested with two flow mode control system could produce 5% NEA at 3 pounds per minute but could produce 8 pounds per minute of NEA if the oxygen concentration was allowed to increase to 9%.

In the analysis of the climb scrubbing process as applied to the C-5B, the following assumptions were made:

o the interconnected matrix of airplane fuel tanks behave thermodynamically as a single (large) tank;

o scrubbing is 100% efficient;

o the NEA flow rate is constant;

o the NEA quality is constant;

o the airplane is fueled with air saturated fuel;

o the limiting flammability criterion is 9% O_2 ullage concentration including the initial (takeoff) condition;

o the scrub gas temperature is equal to the fuel temperature;

o the scrub gas and fuel are in equilibrium at each time increment; and

o the perfect gas laws are applicable.

Airplane related characteristics which entered the calculation of the most severe climb scrubbing requirement were:

o the largest quantity of fuel that could be carried to 40,000 feet on a standard day without cargo is 197,000 lb;

o   the maximum climb rate at which 197,000 lbs of fuel could be lifted to 40,000 feet was that associated with a 63% takeoff fuel load (an initial ullage volume of about 2200 cubic feet);

o   the fuel tank over-pressure relief valve (climb valve) limited the ullage pressure to 1.0 psig; and

o   the airplane routinely landed with inerted fuel tanks containing large quantities of inert gas ullage.

The climb scrub system was operated continuously during the taxi and climb flight segments, but was not required during cruise or descent. (During these otherwise idle periods, the IGG output was used to charge the NEA storage system.) Some of the questions that arose during the climb scrub analysis and the resulting answers:

o   Supposing the airplane has air saturated fuel and a standard atmosphere ullage (as might result after fuel tank maintenance), "How long will it take to restore an inert ullage by ground operation of the IGG?" Since there is no altitude change, and essentially no fuel consumption if the IGG is pressurized from an APU or a ground cart, the time required depends on scrub gas flow and scrub gas quality. Results are shown for NEA_5 at various scrub flow rates in Figure 23. With a 3-lb/min IGG, the time to inert the ullage is in excess of an hour; conceivably acceptable if associated with maintenance activity, but unacceptable as a matter of routine.

o   Suppose the airplane ullage is filled with NEA_6 at the end of the previous mission. If this ullage gas is used to scrub the refueling flow (see Section 3.2.1) by the aspiscrub (or an equivalent) process, the resulting ullage oxygen concentration after refueling would be about 9%, and the oxygen concentration in the fuel dissolved gas about 13.8%.

oo   "What climb scrub flow rate is required to maintain an inert ullage after takeoff, with a 63% fuel load, no cargo, and maximum climb rate to 40,000 feet?" Figure 24 shows various flow rates of NEA_5, and indicates a flow rate that from 3 to 4 lbs/min is required.

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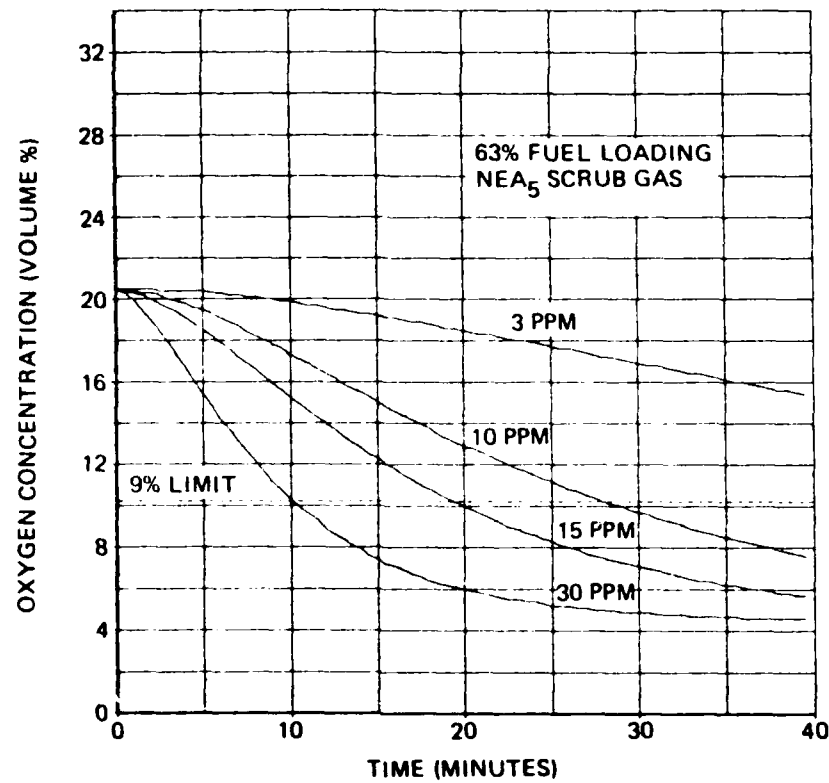
Figure 23. Predicted Ground Scrubbing Results With NEA₅
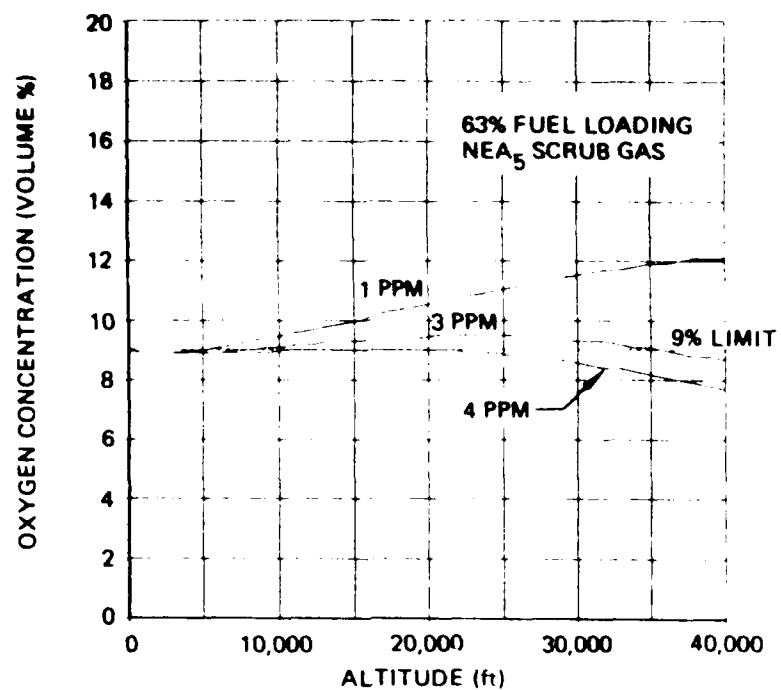
Figure 24. Predicted Climb Scrub Results for C5B Climb From Sea Level
to 40,000 ft, Varying Mass Flows of NEA_5 Scrubbing

oo "If 3 lbs/min of NEA_4 is available for climb scrub, can an inert
ullage be maintained?" The upper curve of Figure 25 shows that this
is a feasible scrub flow rate.

oo "If the ullage was ground purged by flowing NEA_5 through it until
the oxygen content was reduced to 5%, and the available climb scrub
flow rate was 3 lb/min of NEA_5, would the ullage remain inert
during a maximum climb?" The lower curve of Figure 25 shows that a
safe ullage can be maintained.

It may be impractical to use both aspiscrub and climb scrub in combination.
In that case, the fact that the C-5B uses a showerhead fuel tank inlet may be
used to advantage. As the spray of fuel introduced at the top of the tank
during refueling falls through an inert ullage, oxygen will be released by the
fuel droplets, resulting in an increased oxygen content ullage and reduced
oxygen content fuel. The analysis of this case is incomplete, but it is
conceivable that a combination of ground spray scrubbing and climb scrubbing
(augmented by an ullage sweep after refueling if necessary) may provide a safe
ullage during climb.

It was concluded that climb scrubbing is feasible with state-of-the-art IGG
units. Independent of ullage volume, the combination of IGG flow rates and
scrub gas quality that could be used for scrubbing the C-5B fuel tanks,
assuming a maximum ullage concentration of 9% at start of climb, are shown in
Table 3.

Table 3. Scrub Flow Rate Requirements

NEA QUALITY (% OXYGEN)	IGG FLOW RATE (LB/MIN)
3	0.8
4	3.0
5	3.0*

* 4.0 pounds per minute is indicated in Figure 24; 3.0 pounds per minute can
be used if the safe oxygen concentration increases with altitude as shown
in Figure 26.

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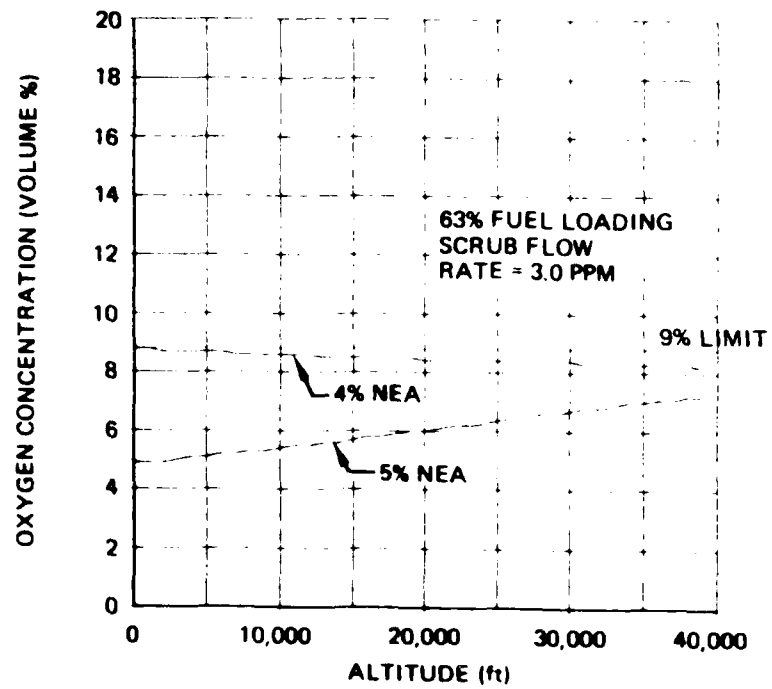
Figure 25. Predicted Climb Scrub Results for C5B Flight From Sea Level
to 40,000 ft, Ullage Sweep With NEA$_5$ Prior to Climb
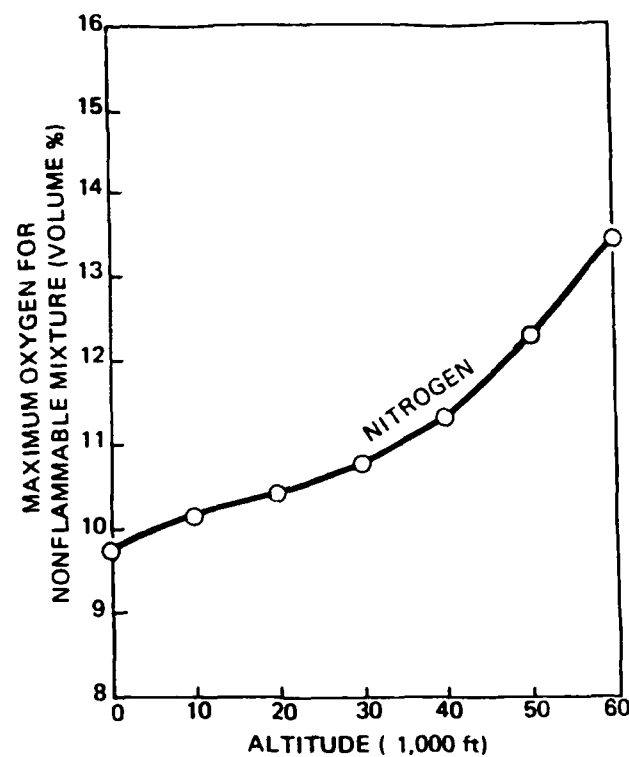
Figure 26. Permissible Oxygen Concentration for N_2 Inerted
Fuel-Air Mixtures AN-F (JP-4) Vapor (Ref. 2)

On the basis of these results, a design flowrate of 3.0 lb/min NEA_5 was selected to minimize IGG size. The calculated ullage oxygen concentration for this scrub flowrate does exceed the 9% limit slightly during climb ($\approx$ 0.5%) as shown in Figure 24, but given the conservatism of the calculation and system weight trade-off considerations, it is an acceptable design choice. In addition, the calculated concentration does remain well within the flammability limit shown in Figure 26, which increases with altitude due mainly to decreasing atmospheric pressure.

3.2.1.2 Aspiscrubbing Analysis

The aspiscrub device installed in the C-5B fleet conserves liquid nitrogen by obviating the need for climb scrubbing. To determine the practicality of aspiscrubbing in conjunction with NEA, an analysis was performed to determine the highest allowable oxygen concentration which could exist in the ullage prior to ground refueling/aspiscrubbing and which would not require climb scrubbing (Figure 27a). Each curve in the figure is labeled as to NEA quality prior to refueling. The ullage oxygen concentration after aspiscrubbing is shown at zero altitude and the increase in oxygen content of the ullage due to gas evolution from the fuel is shown versus altitude. Evidently, the maximum allowable ullage oxygen content prior to refueling is approximately 0.8% if the need for climb scrubbing is to be avoided. Other calculations (Figure 27b) showed that this result is independent of initial ullage volume.

It is not expected that NEA of less than 1% oxygen quality can be produced by either of the two types of IGGs being developed, and oxygen content at the end of descent (initial condition for aspiscrubbing) is likely to be in the range of 3% to 5%. Thus, based on these analytical studies, aspiscrubbing using IGG products cannot ensure against ullage oxygen contents exceeding 9% unless the process is supplemented by other methods.

Ullage wash flow supplementation was chosen for this study. Aspiscrubbing with NEA_5 in the ullage (from the previous flight) at the start of refueling would result in an oxygen concentration of more than 8% at the end of refueling (Figure 28). A wash flow of 1/2 pound per minute of NEA_5 is required to maintain the ullage oxygen concentration within safe limits. This flow rate is evident in Figure 28 which also shows the effect of aspiscrubbing and ullage washing with other NEA qualities.
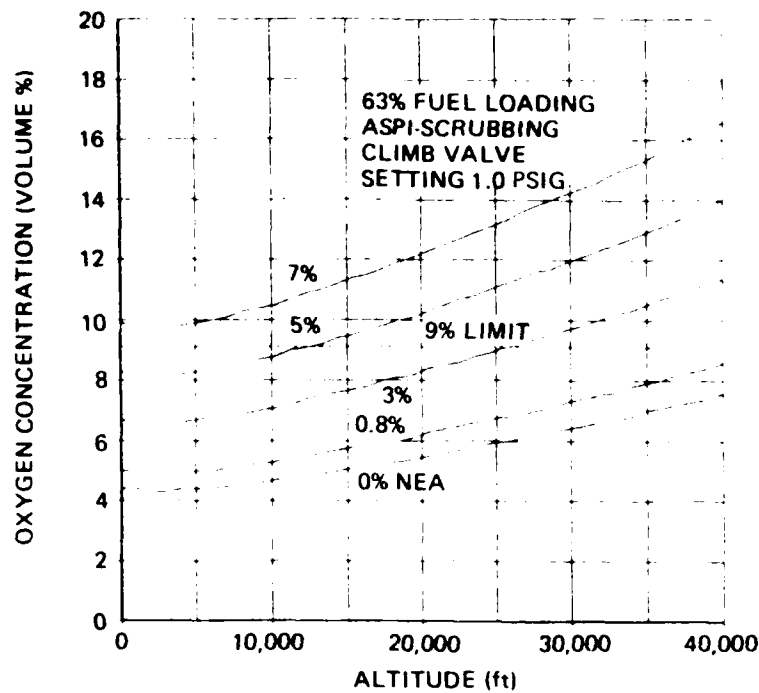
Figure 27a. Predicted Ullage O_2 Concentration Versus Altitude for C5B Flight From Sea Level to 40,000-ft Equilibrium Initial Conditions, Flowing Aspiscrubbing
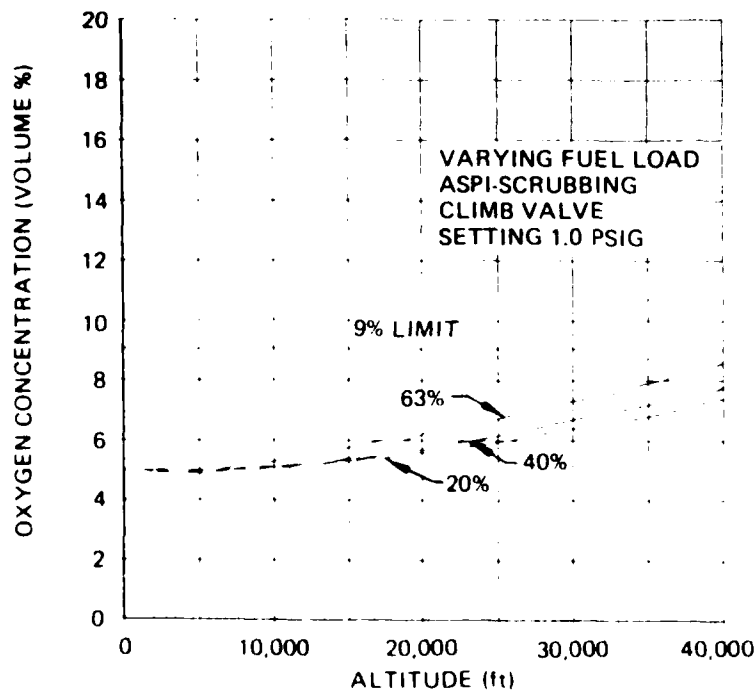
Figure 27b. Predicted Ullage O_2 Concentration Versus Altitude for C5B Flight From Sea Level to 40,000-ft Effect of Fuel Loading

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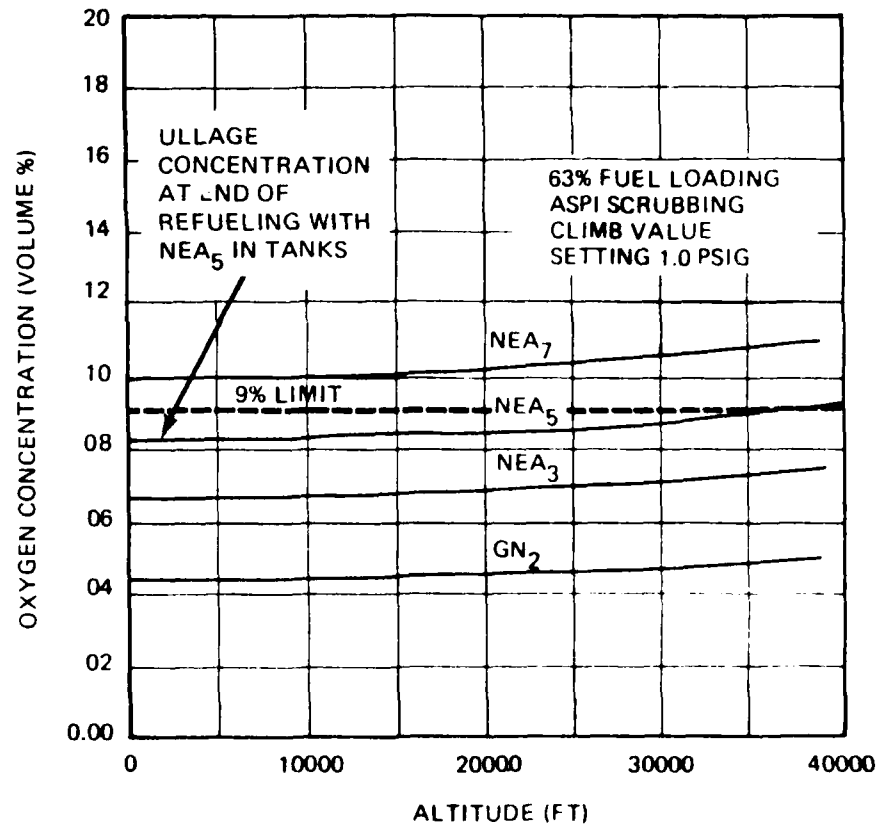
Figure 28. Predicted Ullage O_2 Concentration for Various Equal Aspiscrub
and Wash Flow Qualities at .5 lbm/min

3.2.2 Cruise

During constant pressure altitude cruise, gas evolution from the fuel essentially ceases, and the only need for NEA is to maintain ullage pressure as fuel is consumed. The maximum repressurization flow of NEA required during the cruise segment of the mission occurs at the highest gross weight, when the cruise fuel consumption is highest. The highest aircraft gross weight airplane which can cruise at 40,000 feet was obtained from the Ref. 6, and the resulting fuel consumption rate determined. A flowrate of about 0.16 pounds per minute of inert gas is needed for cruise repressurization. As fuel is consumed, the ullage oxygen concentration will gradually approach the oxygen concentration of the NEA used for repressurization.

3.2.3 Descent

The C-5B LN_2 system is capable of providing fuel tank inerting throughout the design mission, including emergency descents, and a replacement NEA-based system must have a similar capability.

3.2.3.1 Emergency Descent

An emergency descent shortly after takeoff with partially full tanks required the maximum flow rate of NEA. The ullage volume was based on takeoff and climb with a 50% fuel load and no cargo. The lightly loaded airplane has a high rate of climb, reducing the time available to accumulate NEA in the storage system.

Calculations were made (Ref. 6) of repressurization gas requirements for a climb interruption followed by an emergency descent at altitudes of 5,000 feet increments up to 40,000 feet assuming an isothermal recompression.

The results, which are summarized in Table 4, include fuel depletion up to each altitude. The emergency descent calculations reveal that to maintain an ullage oxygen concentration of 9%, at least 274 pounds of stored NEA_5 is needed for full time inerting for an emergency descent from 40,000 feet.

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Table 4. FUEL TANK REPRESSURIZATION REQUIREMENT FOR EMERGENCY DESCENT

ALTITUDE (FT)	CLIMB TIME (MIN)	RAPID DESCENT TIME (MIN)	FUEL QUANTITY AT RESPECTIVE ALTITUDE (LB)	TOTAL QUANTITY OF NEA REQUIRED FOR DESCENT AT ULLAGE OXYGEN CONCENTRATION	
				<9% (LB)	<12% (LB)
S.L.	0.0	0.0	159,000	0.0	0.0
5,000	1.5	0.7	157,800	35.7	0.0
10,000	3.0	1.4	156,550	75.2	0.0
15,000	5.0	2.0	155,050	113.4	25.0
20,000	7.0	2.6	153,550	149.6	49.4
25,000	10.0	3.1	152,050	184.1	72.2
30,000	13.0	3.45	150,550	217.3	94.0
35,000	17.0	3.95	149,050	249.3	114.5
40,000	25.0	4.5	146,050	273.5	130.8

Assumptions:

o total fuel tank volume is approximately 6700 cubic feet

o 50% fuel load at take-off, no cargo load

o fuel usage during climb taken into account; descent time based on gross weight at time descent initiated

However, the ground rules (Section 3.0) allowed the dive valves to open during an emergency descent if the oxygen concentration did not exceed 12%. The calculations based on the 12% criterion show that the amount of stored NEA_5 required is reduced to 131 pounds. This illustrates the significant weight savings possible by relaxing the 9% oxygen limit.

3.2.3.2 Standard Descent

The NEA required for a standard descent from 40,000 is shown as a function of elapsed time from start of descent in Figure 29. For the conditions shown, about 425 pounds of NEA were required for descent repressurization. The basis of the computation is the same as that presented in Ref. 7 for the LN_2 system, i.e., a descent with a 15% fuel load and 400,000 lb gross weight. Since 8 hours were available for NEA production prior to the standard descent and the production rate was 3 pounds per minute, the amount of stored NEA provided sufficient inert gas for repressurization (the dive valves remained closed and the tanks inerted throughout the descent).

The quality of the NEA used for tank repressurization is not critical if the oxygen concentration is less than 9%. This is illustrated by Figure 30 which shows the final ullage oxygen concentration for NEA_7, NEA_5, NEA_3 and GN_2 as a function of the altitude where descent was initiated. Note that as the descent initiation altitude increases, the final ullage oxygen concentration approaches the oxygen concentration in the repressurization gas.

3.3 C5-B ON-BOARD INERT GAS GENERATOR SYSTEM DESIGN

Four basic factors were considered in designing the OBIGGS fuel tank inerting system for the C-5B airplane. These were:

o   conditioning of supply air for the air separation modules;
o   comparison of permeable membrane with molecular sieve air separation modules;
o   the high pressure compressor and storage tank for inert gas storage; and
o   the inert gas distribution system.

Each of these is discussed in detail below.
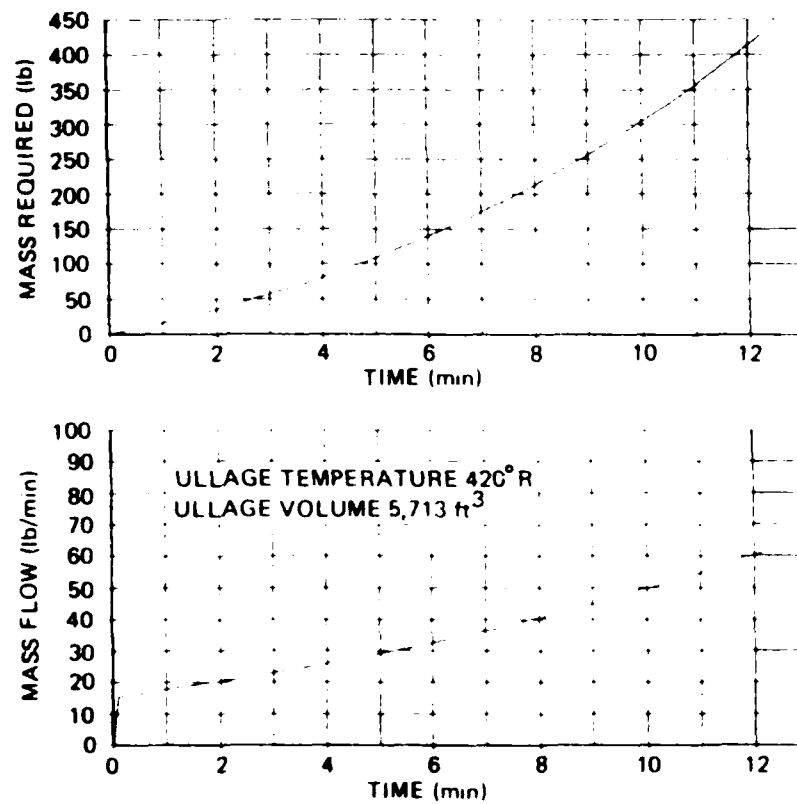
Figure 29. NEA Required for Descent From 40,000 ft at End of Mission
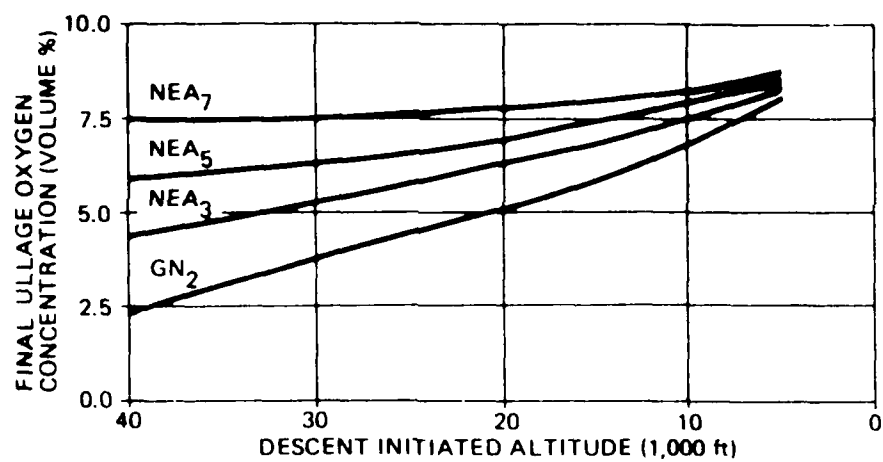
Figure 30.   Final Ullage Concentration as a Function of Altitude at Which
              Descent was Initiated Using NEA Quality as a Parameter

3.3.1 Supply Air Conditioning

Air separation modules require a source of pressure and temperature controlled air. The most convenient source is engine compressor bleed air which is suitably conditioned.

A variety of techniques are available to supply the conditioned air because systems developed for environmental control systems are applicable. The problem is to select the system with the minimum impact on the airplane, recalling that weight, volume, and bleed air penalties are all involved. The following discussion provides the rationale for selecting the system on which these C-5B studies were based.

3.3.1.1 C-5B Baseline IGG Air Supply System

The baseline C-5B IGG Air Supply System selected for this study is shown in Figure 31. This system was selected following trade studies which included a dedicated bleed air source system, cabin air cooled system, and utilization of air cycle machine compressor discharge air. This system is a refinement of the boost compressor system described in Ref. 6. The other systems described in Ref. 6, including the simple cycle system, bootstrap system, and vapor cycle system, were discarded either because of weight, high bleed air usage, or complexity.

The system shown in Figure 31 receives bleed air from the C-5B bleed air manifold; the pressure in the manifold varies from 92.5 psia at takeoff to 18.25 psia for cruise at 40,000 feet. The MSIGG pressure regulator was set at 50 $\pm$5 psig and the temperature regulator at 50 $\pm$10°F. These settings were based on the MSIGG pressure/temperature sensitivity curves and the sensitivity of Environmental Control System (ECS) weight/energy extraction to MSIGG interface conditions.

The analysis showed that the worst case low pressure supply would be 45 psig and highest supply air temperature would be 60°F. The MSIGG air supply system was sized for these conditions.
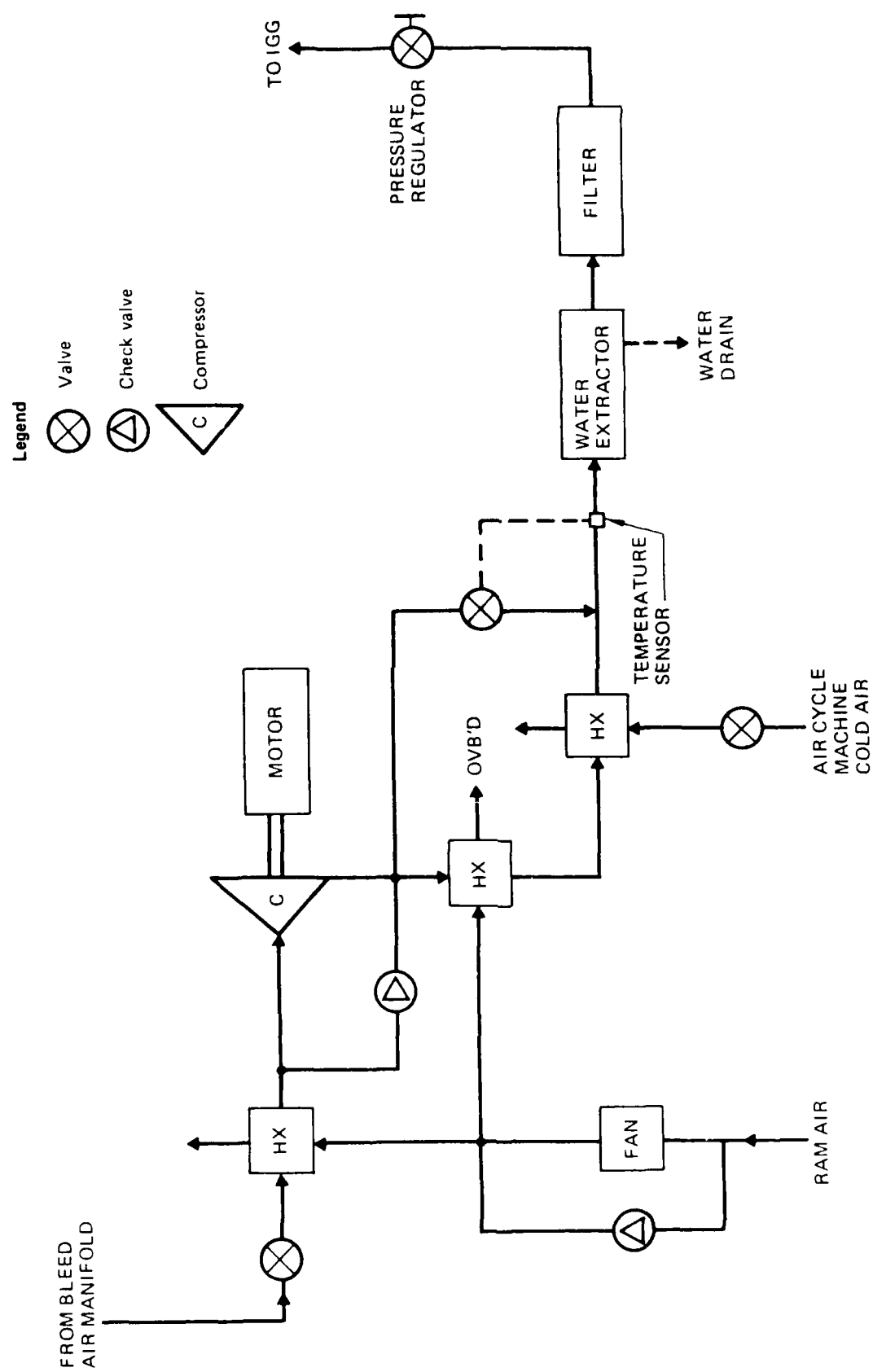
Figure 31. Baseline C-5B IGG Air Supply System

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The PMIGG supply air system differed only in the pressure regulator and temperature control settings. The pressure regulator was set at 100 ±5 psig and temperature regulator at 75°F. A variable speed motor would be required to provide a constant pressure to the IGG with varying pressures in the bleed air manifold. A second approach would be to use a pressure regulator upstream of the boost compressor with a constant speed motor. The pressure regulator would prevent the compressor from going into surge by limiting inlet pressures to 20 ±2 psig. The second approach was chosen because of its simplicity and lower estimated costs.

The trade study of the number of PMIGG air separation module units required as a function of inlet pressure was made. This study showed that 11 units of the existing CH-53E helicopter design at a total weight of 429 pounds would be required for a stored gas OBIGGS if the inlet pressure to the PMIGG was 60 psig. The number of units would be reduced to 6 at a total weight of 234 pounds if the inlet pressure was increased to 100 psig. The air compressor size and power requirements would increase 40%, but the reduction in the number of PMIGG units would more than compensate for this increase.

Ram air was provided by tapping into the C-5B ram air plenum chambers. Cooling air was ducted through two parallel heat exchangers. The ram air then exited through the C-5B exhaust duct. A cooling air fan was provided to maintain sufficient air flow during taxi-out and initial stages of climb. When the ram air pressure was sufficiently high, the fan was turned off and the air partially bypassed through a check valve.

The IGG supply air then entered the air cycle machine (ACM) cold air heat exchanger. The cold air for the heat exchanger was tapped off the ACM compressor ahead of the water separator to take advantage of the cooling effect associated with re-evaporation of the entrained moisture in the air. The ACM cold air was used during takeoff and climb when the MSIGG supply air was warmer than 75°F. During takeoff and climb, the ACM output was very high so that extraction of air needed for IGG supply should not significantly degrade C-5B air conditioning performance. Should the supply temperature decrease below the sensed settings, the temperature controller would maintain the supply air temperature at 50 ±10°F for the MSIGG and 75 ±10°F for the PMIGG.

A highly efficient water separator was installed to remove moisture from the supply air. A maximum moisture content of 25 grains per pound of dry air would be passed to the filter. The filter would trap 99.95% of dust and remaining moisture particles in the system greater than 0.6 microns. The ram air/ACM air exit temperature would still be cold enough to provide interstage cooling of the IGG compressor.

The IGG/ECS interface conditions are given in Table 5 for both the PMIGG and MSIGG. The resources required ɔ supply air at required interface conditions are also shown. The power requirements to drive the boost compressor was high due to the amount of compression required to meet the 50 psig minimum pressure requirement for the MSIGG and 100 psig requirement for the PMIGG. A system with a lower pressure rise does not result in less power consumption since the bleed air flow rate to the IGG must be increased to maintain the same product gas flow rate.

The estimated air supply system weights breakdown for the MSIGG and PMIGG is shown in Table 6. The total weight for the PMIGG air supply system is 115 pounds; the corresponding MSIGG weight is 148 pounds.

The estimated volumes for the air supply unit and ducting is shown in Table 7. The volume for the air supply unit is the total outline drawing volume and not the summation of individual component volumes.

TABLE 5.   BASELINE C-5B IGG AIR SUPPLY SYSTEM PERFORMANCE

	PMIGG		MSIGG	
	TAKEOFF	40,000 FT	TAKEOFF	40,000 FT
IGG/ECS INTERFACE				
FLOW RATE TO IGG ∿ LBS/MIN	11.0	11.0	18.5	18.5
PRESSURE ∿ PSIG	95 +5	95 +5	50 +5	50 +5
TEMPERATURE ∿ DEG. F	75 +10	75 +10	50 +10	50 +10
RESOURCES REQUIRED				
BLEED AIR ∿ LBS/MIN	11.1	11.1	18.6	18.6
RAM AIR ∿ LBS/MIN	46	46	65	65
POWER ∿ KW	31.0	28.0	3.1	30.0
ACM AIR ∿ LBS/MIN	13.	0	19.	0
% C-5 BLEED AIR EXTRACTION	1.9	4.3	3.1	7.2
% C-5 ACM AIR EXTRACTION	2.2	0	3.1	0

TABLE 6. BASELINE C-5B IGG AIR SUPPLY SYSTEM EQUIPMENT
- ESTIMATED WEIGHTS -

	QUANTITY PER APL.	PMIGG WEIGHT SHIPSET (LBS)	MSIGG WEIGHT SHIPSET (LBS)
RAM AIR DUCT	1	19.0	27.0
GROUND COOLING FAN	1	4.2	6.0
CHECK VALVE, RAM AIR	1	2.9	4.2
RAM AIR HEAT EXCHANGERS	2	20.0	28.5
ACM HEAT EXCHANGER	1	6.6	9.4
AIR COMPRESSOR	1	9.0	8.5
MOTOR	1	16.0	15.0
SUPPLY AIR VALVES	2	1.8	2.7
PRESSURE REGULATOR	1	1.9	2.1
MODULATING VALVE	1	1.3	1.9
TEMPERATURE SENSOR	1	.12	.12
TEMPERATURE CONTROLLER	1	0.5	0.5
WATER EXTRACTOR	1	1.0	1.3
PRESSURE REGULATOR	1	1.9	2.1
FILTER	1	2.0	2.9
SUPPLY AIR DUCTING SET	1	5.0	7.0
WIRING	-	8.4	12.0
THERMOSTAT, COMPRESSOR DISCHARGE	1	1.2	1.2
INSTALLATION	-	12.5	15.5
TOTAL WEIGHT		115	148

TABLE 7. C-5B IGG AIR SUPPLY SYSTEM VOLUMES

	MSIGG AIR SOURCE	PMIGG AIR SOURCE
AIR SUPPLY UNIT $\sim$ FT^3	3.7	2.0
RAM AIR DUCTING $\sim$ INCHES	7.0	6.0
BLEED AIR DUCTING $\sim$ INCHES (UPSTREAM OF COMPRESSOR)	2.25	1.75
BLEED AIR DUCTING $\sim$ INCHES (DOWNSTREAM OF COMPRESSOR)	1.25	.75

3.3.1.2 Alternate C-5B IGG Air Supply System

An alternate air source system utilizing separate 16th stage bleed air extraction was investigated. A schematic of the system is shown in Figure 32. Two bleed air sources were required to ensure air source availability with one engine out or a bleed system failure condition.

The air source was extracted from the duct which routes air to C-5B augmenter valve. The bleed air passed through a pressure regulator which reduced the bleed air pressure to 125 psia maximum for the PMIGG system or 75 psia maximum for the MSIGG system. A precooler cooled the 16th stage bleed air to $450^\circ F$ maximum by using engine fan air as a heat sink. Firewall shutoff valves allowed either bleed air system to be shut off by a switch on the air conditioning panel. They also acted as overheat valves which prevented the bleed air from exceeding $500^\circ F$ in case of pressure regulator failure. A check valve prevented reverse flow into an engine. A sketch of the engine bleed air system installation is shown in Figure 33.

The advantage of the alternate system is that it eliminated the air supply compressor, in the case of the MSIGG system, or it reduced the size of the PMIGG compressor. The disadvantages of a dedicated bleed air system are: reduced reliability, increased weight and increased complexity. The disadvantages, in this case, far outweighed the advantages; therefore, further investigation of the bleed air supply system was discontinued.

3.3.1.3 Alternate C-5B Heat Sink Source

The use of cabin air as a heat sink source was investigated. The cabin air temperature can be as high as $80^\circ F$ during hot day ground conditions and $75^\circ F$ during flight conditions. Ram air temperature during 40,000 ft. hot day cruise is about $4^\circ F$, so it provides a much colder heat sink than cabin air. Cabin air alone could be used as a heat sink for PMIGG, but additional cooling from the ACM would be required for the MSIGG unit. Also, an air conditioning pack failure poses a potential problem. Since 35% of inflow into the cabin will be used for cooling the PMIGG air source with one pack operating, there may be insufficient airflow to pressurize the aircraft to the selected levels.
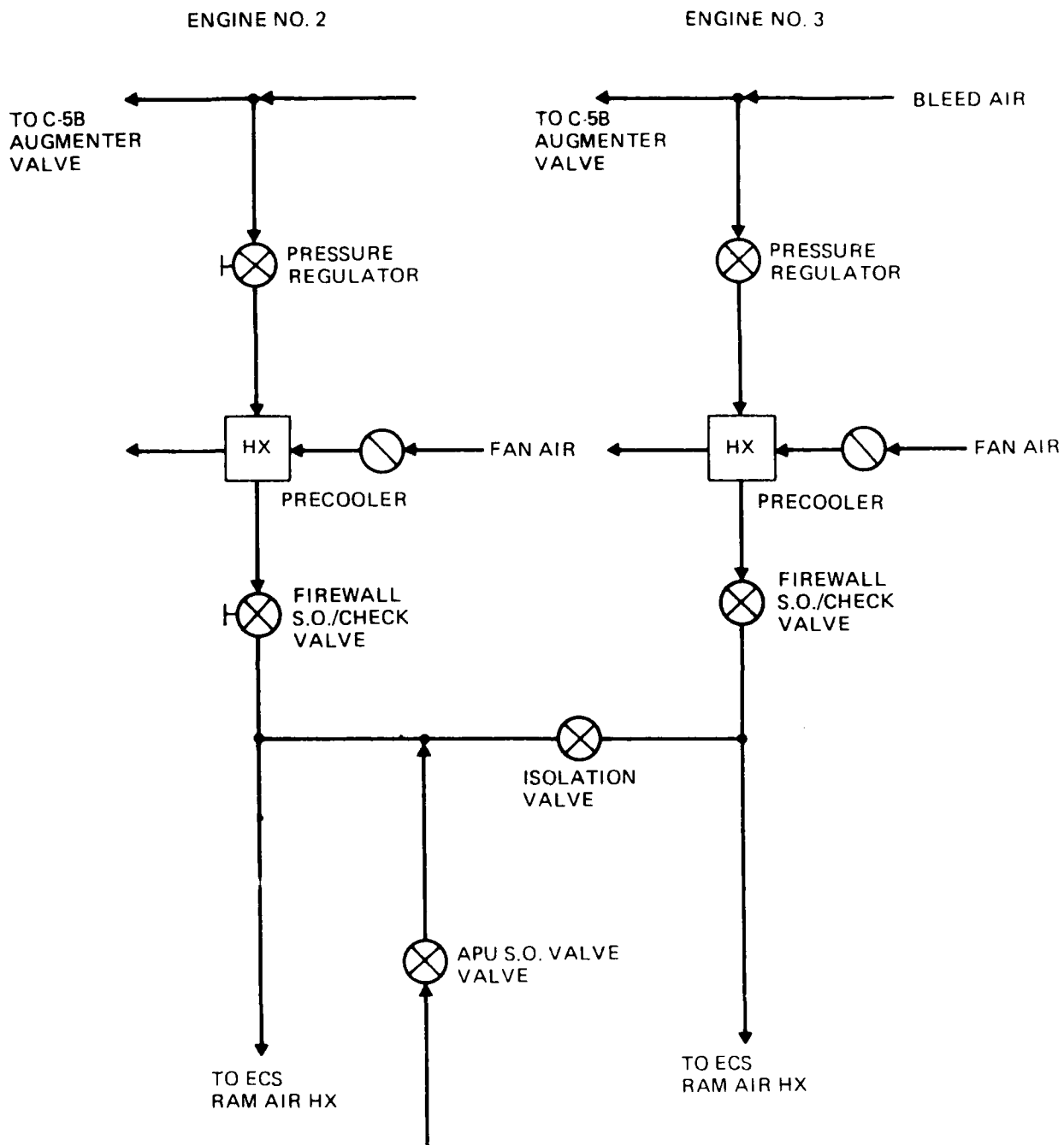
Figure 32. C-5B ECS/Fuel Inerting Air Source

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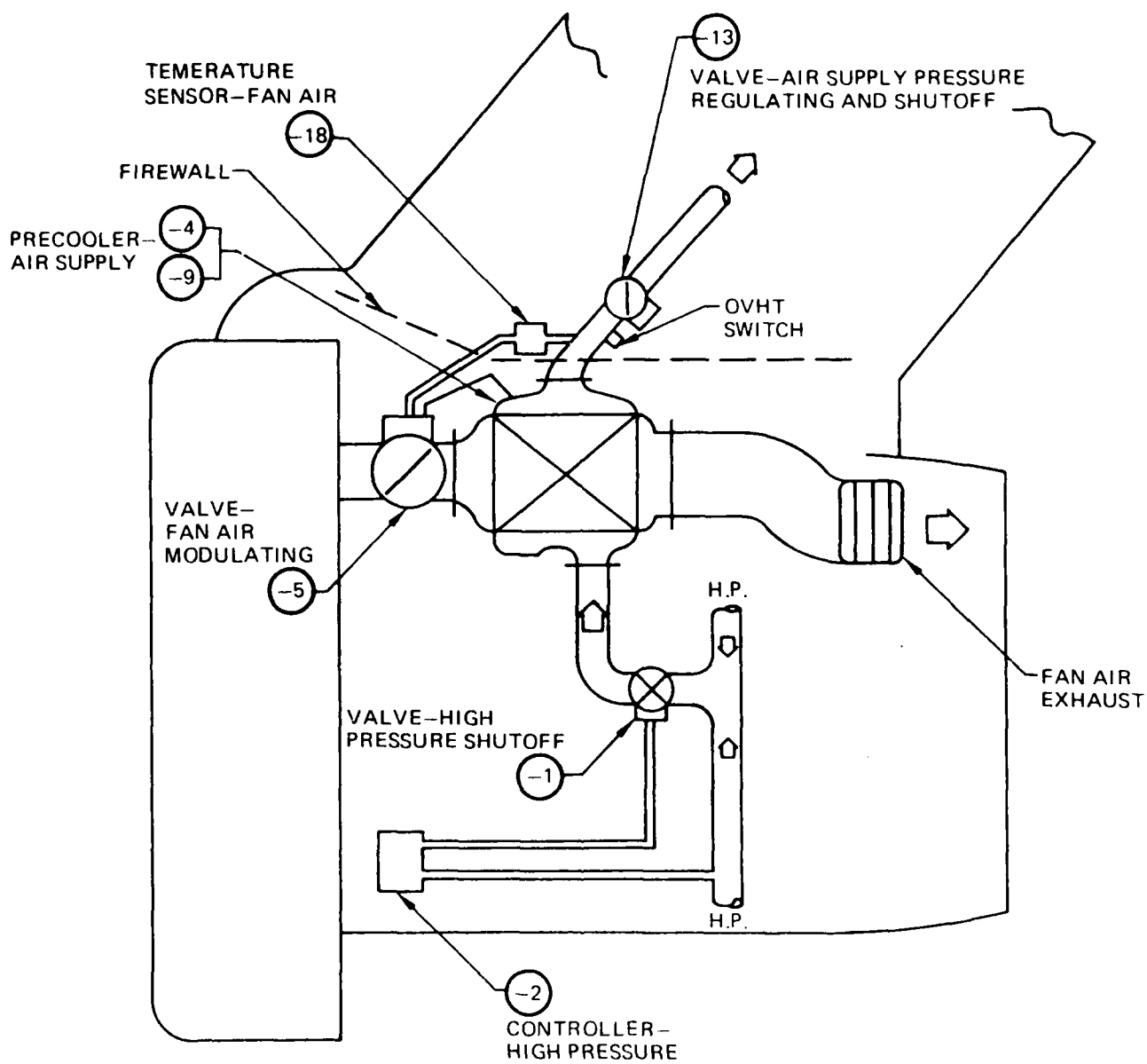
Figure 33. Bleed Air System Installation

3.3.1.4 New C-5B IGG/ECS Air Supply System Design

At the time this study was performed it was assumed that the OBIGGS could be designed without the constraints of the current airplane, which would allow improvements over the C-5A design. The exclusive use of only high stage bleed air for the ECS and IGG was not recommended since IGG requirements represent only 1.9% to 7.2% of total ECS requirements as shown in Table 5. The penalty for using only high stage bleed air would be excessive. The use of a two stage bleed system similar to that used on most commercial aircraft would be an improvement over the present C-5B system. The bleed air would be extracted from 8th stage during takeoff, climb, and cruise. High stage bleed would only be used during descent and holding conditions. Boost compressors would still be required, but the compression ratio and hence the power required would be reduced, resulting in an estimated 21% to 28% reduction in power input to the compressor.

The ram air system for the IGG would also be integrated with the ECS; thus, separate ram air ducting and a turbofan would not be required. A high pressure water separator system and recirculation type air cycle pack currently installed in the Boeing 757/767 aircraft would be used. This type of system would use less bleed air and supplies much colder air, thereby reducing ACM air requirements when compared with the C-5B refrigeration system. The IGG requirements would be incorporated into the ECS design; consequently, no ECS or electrical system performance degradation would result.

3.3.2 Extension of Inerting System to Fire Fighting

The ground rules for this study were to optimize the C-5B OBIGGS for fuel tank inerting and to investigate extending the system to provide fire protection with NEA. For potential fire protection applications, a trade-off between Halon and NEA was required.

The design requirements for the NEA fire suppression system (FSS) were the same as those imposed on the LN_2 system:

o   the extinguishant flow was required to reduce the oxygen percentage by volume in the zone to 9% or less within 10 seconds; and

o the addition of extinguishant could not cause the maximum allowable pressure in the zone to be exceeded.

On this basis, NEA requirements were defined for Zones 1 through 12 (Figure 13) and compared with Halon requirements.

3.3.2.1 Fire Protection Agent Selection

The evaluation considered fire protection for the engine nacelle, cargo volumes, wheel wells, habited volumes, and certain other dry bays. The current C-5A protection system offers protection to these areas; a rationale for not protecting the remaining dry bays in the airplane is given in the C-5A hazard analysis (Appendix F, Reference 8): "... the decisions not to protect them were based on weighing the probability of combustion occurring [in these areas] against the ability to get enough agent to the fire to extinguish it, the ability to install the fire fighting capability, and the weight increase [involved]." For example, the wing leading edge dry bays outboard of the No. 1 and No. 4 engines contain no flammable liquid lines, and fuel can only enter the region by leakage through the front spar. Since there are few potential ignition sources in the vicinity, no protection was provided.

While the use of NEA in the zones currently protected by LN_2 was considered feasible, replacement of Halon protection by NEA was difficult or impractical. Though NEA could extinguish a fire in the main cargo bays, the quantity of agent required would be very large. For example, if each pound of air in the largest cargo bay (Zones 13, 14, and 15 in Figure 19) was replaced with a pound of NEA, about 3500 pounds of NEA would be required for fire extinguishing in the 46,652 cubic feet volume. A Halon 1301 quantity of only 1190 pounds is currently used to protect these zones. In addition, the time required to discharge the NEA does not compare favorably with the 5 seconds response claimed for Halon. It is clear that Halon is the preferable extinguishant for the main cargo bays.

The use of Halon 1301 was also indicated for the somewhat smaller center wing and avionics bays (Zones 16 and 17, Figure 13). The rapid discharge feature of Halon makes it preferable to either LN_2 or NEA because of the proximity of habited zones. High ventilation rates in these zones are likely to prevent

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practical inert gas flow rates from reducing the oxygen concentration in the vicinity of a fire long enough to extinguish the fire, especially with fixed discharge nozzles locations.

3.3.2.2 Fire Suppression Systems

Establishing the appropriate quantity of extinguishing agent for a compartment involves several considerations:

- o identification of the potential combustibles and ignition sources present;
- o the availability of test data with which to compare the potential fire types;
- o compartment volume, available vent area, ventilation airflow, and allowable overpressure; and
- o delivery system design.

Operation of an NEA fire suppression system (FSS) is basically the same as the LN_2 FSS system described in Section 3.1.2.1. When the fire suppression system is activated, the line between the NEA storage bottle and fire zone is pressurized. When the line pressure reaches the flow pressure required, the zone valve opens, discharging NEA into the zone. A constant mass flow of NEA was assumed for ease of calculation, and for efficiency. Unlike the LN_2 mass flow, which would be difficult to control due to the transients caused by two phase flow of nitrogen, the flow of NEA could be easily controlled for optimum performance.

The test results reported in Ref. 6 indicate that between 50% and 100% added NEA is required for fire extinguishment at ventilation rates encountered in airplane compartments, depending on fire type. While NEA requirements might be reduced if ventilation rates and fire types are considered, the maximum NEA quantity needed in each compartment was used for FSS sizing to insure conservatism.

3.3.2.3 Compartment and Engine Nacelle Fire Suppression Requirements

The flowrates and quantities of NEA required for each zone were determined, and from them, the quantity of NEA which had to be reserved for fire

protection was established. In the analysis, two possibilities were considered for the behavior of the NEA when it was injected into a compartment:

o   air present in the zone at the time of NEA injection was driven out in a piston-like manner, and vented from the compartment with no mixing with the NEA,

o   each unit volume of incoming NEA mixed completely with the air in the compartment, and the vented flow had the composition of the mixture.

Thorough mixing is unlikely; it is more likely that a combination of the piston and mixing processes will occur. The flowrate required to reduce oxygen concentration to 9% in 10 seconds was computed for each of the twelve zones (Figure 13) to be protected under both assumptions, with results shown in columns (e) and (f) of Table 8. Since the amount of NEA required is greater in the mixing assumption, this quantity was used for conservatism in determining fire suppression quantity requirements. For easy reference, the compartment volumes, vent areas, and allowable overpressures are repeated in columns (b), (c), and (d). In addition to fire extinguishment requirements (oxygen reduction), structural and physical constraints are of importance in determining the appropriate NEA flowrates for fire suppression in each zone. The highest mass flow that could reasonably be used for the fire suppression system was 4.5 pounds per second, and line sizing calculations were based on this value.

The volume, vent area, and allowable overpressure for each zone were considered in determining the flowrate of NEA that could be used at any altitude at which the aircraft is likely to operate without exceeding the allowable zone overpressure. These flowrates are listed in Table 8 column (g). The agent flow was assumed to continue for a total of 30 seconds, 20 seconds beyond the time allowed for oxygen concentration reduction, to help ensure fire extinguishment through oxygen dilution and the cooling effect of the agent.

Due to structural considerations and resultant NEA flowrate limitations, it was generally not possible to reduce the calculated oxygen concentration in the zone to the 9% limit in the 10 second specification, or even in the designated 30 second agent flow time. This deficiency is indicated in Table 8, column (h); if the 9% limit at sea level was reached in less than 30

TABLE 8.

NEA$_5$ FIRE SUPPRESSION SYSTEM REQUIREMENTS

(a) ZONE	(b) VOLUME (FT^3)	(c) VENT AREA* (IN^2)	(d) ΔP_{MAX} (PSIG)	(e) 10 SECOND $\dot{m}$ NEA$_5$ (LB/SEC) NO MIXING	(f) 10 SECOND $\dot{m}$ NEA$_5$ (LB/SEC) MIXING	(g) MIXING $\dot{m}$ MAX (LB/SEC)	(h) MIXING TIME AT SEA LEVEL (SEC)	(g) × 30 SEC NEA REQUIRED (LB)
1,4 A	118	41.0	1.0	0.9	1.2	1.2	10	36
B	231	11.42	5.5	1.7	2.8	1.8	15	54
2,3 A	460	28.5	1.0	3.4	5.5	1.3	30	39
B	374	31.2	0.5	2.8	4.1	0.9	30	27
5	640	46.8	1.0	4.8	7.4	2.2	30	66
6	1809	301.44	0.3	13.4	19.0	4.5	30	135
7	2243	301.44	0.3	16.7	23.2	4.5	30	135
8	2140	136.0	1.0	15.9	25.0	4.5	30	135
9	2140	136.0	1.0	15.9	25.0	4.5	30	135
10	1873	113.0	1.2	13.9	22.0	4.5	30	135
11	313	23.2	1.0	2.3	3.5	1.1	30	33
12	313	23.2	1.0	2.3	3.5	1.1	30	33

* REFERENCE 1

seconds, that time was shown; if not, 30 seconds was shown. In some cases the quantities shown in the last column of Table 8 are less than the LN_2 supplied to the same zone (Table 1). This discrepancy is due to the factors just discussed, i.e., line size and compartment limitations.

In only one case, Zone 1, could the 9% limit be reached at sea level within 10 seconds; Figure 34 shows O_2 concentration in this zone versus time with an extinguishant injection flowrate of 1.2 lb/sec. As can be seen, the sea level case is the most difficult, and the necessary flow time to approach the 9% O_2 limit is lower at higher altitudes. Similar data is shown for Zone 5 in Figure 35; for the maximum allowable flowrate of 2.2 lb/sec, the sea level O_2 level decreases to 9% at the end of 30 seconds, and sooner at higher altitudes.

Since the maximum flowrate of any quality NEA is restricted by zone overpressure limitations, the allowable flow of higher quality NEA, NEA_3 for example, is the same as the NEA_5 flow. Figure 36 shows the effect of adding 4.5 lb/sec of NEA_5 to Zone 7, and Figure 37 shows the effect of adding the same flow of NEA_3. The time to approach 9% oxygen is, of course, shorter with NEA_3. Results of calculations performed for each of the other large zones were similar to those shown in Figure 35; for the design flowrates selected (column (g), Table 8) the oxygen concentration at sea level was always 12% or less at the end of the 30 second flow time.

Summarizing, the utility of NEA as an extinguishant is limited (by pressurization constraints) to the flowrates shown in column (g), Table 8, and frequently prevents attainment of 9% O_2 concentration within the 10 second goal. Nevertheless, fire extinguishment within 10 seconds is probable for the following reasons, not considered in the analysis:

- o the assumption of uniform mixing of the extinguishant is conservative;
- o oxygen consumption by the fire has been neglected; and
- o NEA stored routinely for emergency fire and inerting protection could be lower in oxygen content than the NEA_5 used in the calculations because the OBIGGS could be tailored to produce NEA with low oxygen concentrations for storage purposes.
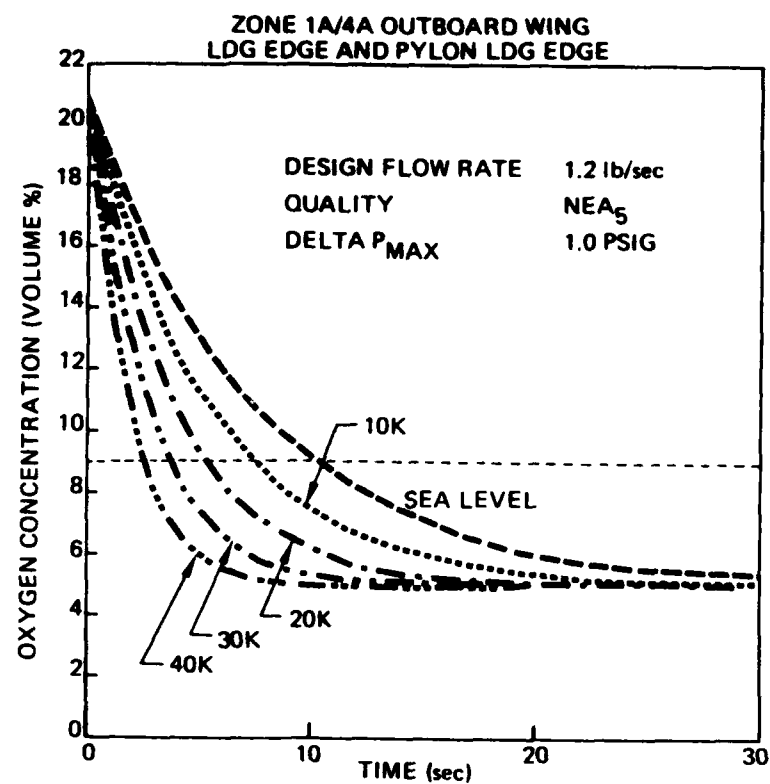
Figure 34. *Zones 1A/4A Volume Percent O_2 as a Function of NEA_5 Injection Time*
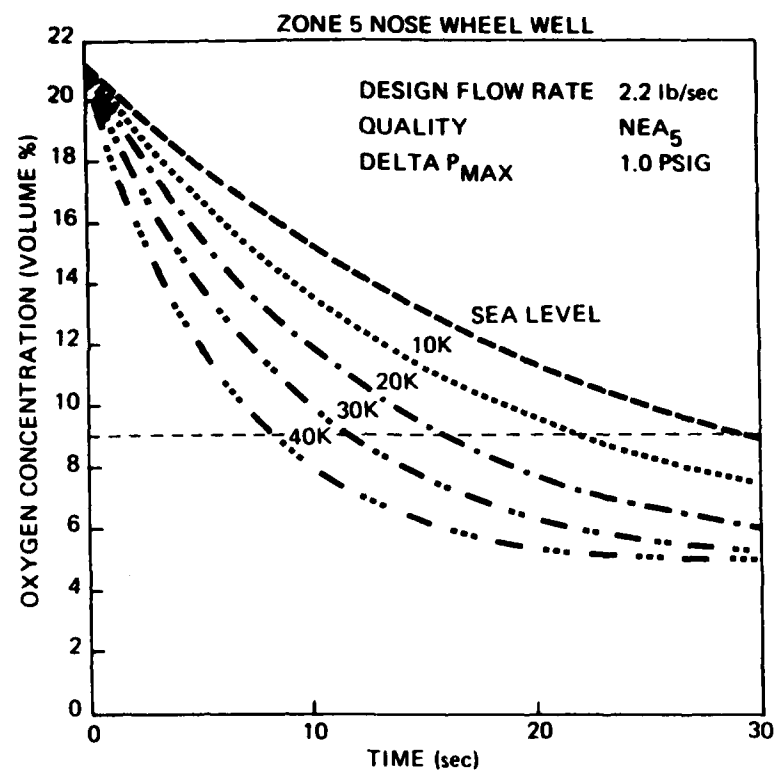
Figure 35. Zone 5 Volume Percent O_2 as a Function of NEA_5 Injection Time
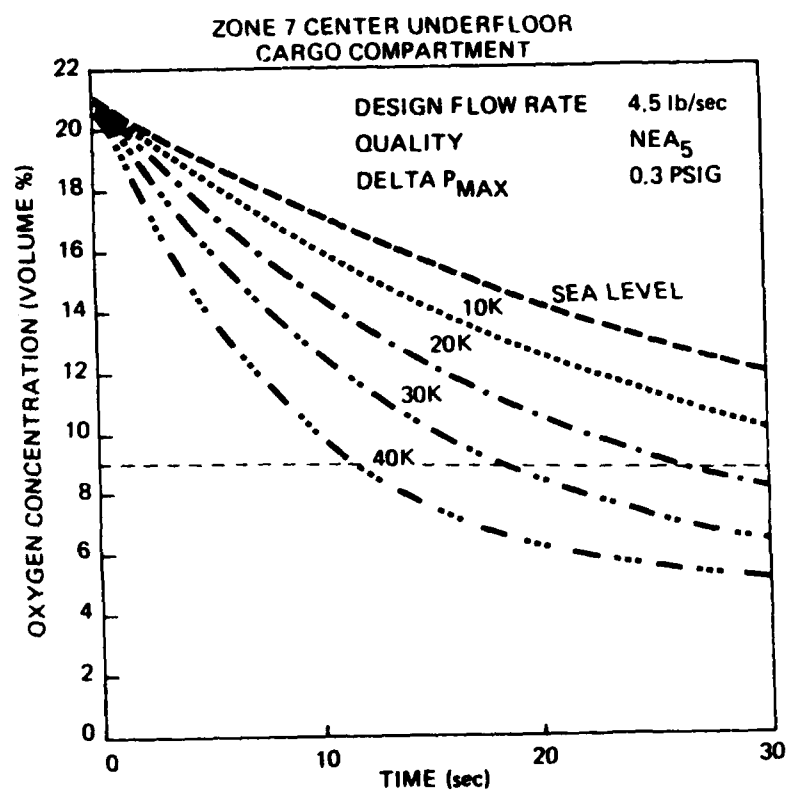
Figure 36. Zone 7 Volume Percent O_2 as a Function of NEA_5 Injection time
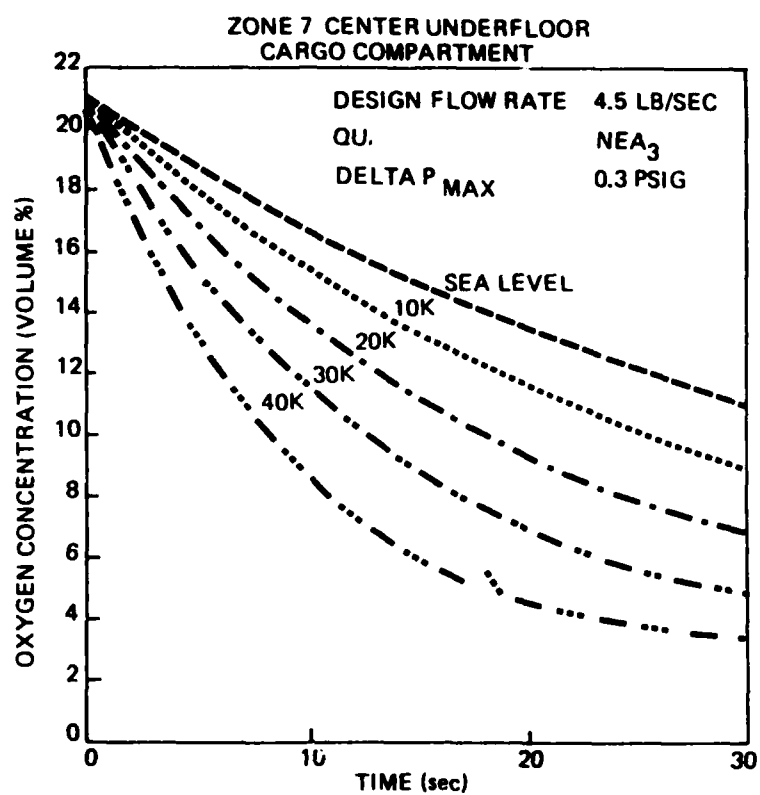
Figure 37. Zone 7 Volume Percent O_2 as a Function of NEA_3 Injection Time

Recall that the analysis does assume a continuous flow of agent, which can be accomplished with a gaseous agent with a pressurized system and flowrate control, and which will serve to quickly reduce the oxygen concentration.

As with the inertant used for fuel tank repressurization, demand flow rates for fire suppression are much higher than can be provided by existing IGG units, reinforcing the need for NEA storage. The quantity of NEA_5 reserved for compartment fire suppression is 135 pounds, enough to provide one 30-second application to the largest zones, and 2 to 4 applications of extinguishant to the smaller zones.

It is of interest to note that times of 25 seconds or more to reach the 10% O_2 level were accepted in the design of the LN_2 FSS. The design LN_2 flowrate and time to reach 10% O_2 concentration at each flowrate, as well as the mass flow needed to reach the 10% level in 10 seconds are shown in Table 8.

NEA was also used for engine nacelle fire protection (Zones 18 and 19, Figure 20) in the integrated inerting/fire suppression system preliminary design for comparison with the existing halon system. Information obtained from General Electric on ventilation flowrates in the TF-39 engine nacelle indicates that these flows are:

o 4.2 pounds per second maximum flowrate at sea level take-off conditions; and
o 1.2 pounds per second idle flow rate.

In case of an engine fire, the standard procedure is to shut down the engine and to shut off the flow of all combustible fluids to the engine before discharging nacelle extinguishants. Ventilating air flow is derived from fan bleed air; thus when an engine is shut down, the ventilating air flow is reduced to that associated with a "windmilling" engine fan flow. No actual data was available on the flowrate through the nacelle for the windmilling condition. However, 10% of the sea level maximum flow was felt to be a conservative estimate for calculating agent requirements. Thus, based on a ventilation air flow rate of 0.42 pounds per second, an NEA_5 flow of 0.92 pounds per second is sufficient to reduce the oxygen concentration of the mixture of ventilation air and NEA_5 to 9%. In addition to the fire extinguishing action of reduced O_2 concentration, the added flow of the NEA

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serves to increase local air velocities improving the effectiveness of the fire extinguishant. (This velocity effect is shown in test results presented in Ref. 9.) As for the compartments, a fire suppression agent application time of 30 seconds was selected, requiring a total of 28 pounds of NEA_5 per application. Since 135 pounds is reserved for compartment fire protection, there is sufficient NEA_5 available to provide five separate 30 second applications of extinguishant to an engine nacelle fire at the minimum NEA stored gas condition. The 30 second agent application time is intended to provide for rapid fire extinguishment followed by a cooling period to help reduce instances of fire re-ignition, a particular problem in engine nacelle fires.

3.4 Comparison Studies

A comparison of using Halon and NEA for fire suppression for various zones on the C-5B airplane is summarized in Table 9. The table reveals that the total system weight would be reduced by increasing the use of NEA. However, the ground rules (Section 3.0) led to a design in which as little as 167 pounds (Section 3.3.1.3.1) of stored NEA may be available for fire suppression. Referring to Table 9, only the baseline system and alternative systems 1 and 2 would be compatible with the minimum of 167 pounds of stored NEA. Since the payoff in terms of weight savings was almost negligible for these systems, the baseline (Halon only) system was specified for subsequent comparisons with other systems.

3.5 Resulting C-5B OBIGGS Design

Although the OBIGGS has not been flight tested, extensive laboratory and flight simulation testing indicate that OBIGGS implementation on the C-5B airplane would not present any large technical risks. The data base developed by this testing allows the required system to be realistically sized and airplane penalties to be predicted. Totally accurate cost comparisons are difficult because the LN_2 and foam systems are mature systems, whereas the OBIGGS is still in the developmental stage. Nevertheless, such comparisons based on OBIGGS projected costs are meaningful in guiding development of OBIGGS technology.

TABLE 9.

COMPARTMENT FIRE SUPPRESSION NEA_5 vs. HALON ALTERNATIVES

	ZONES 1 – 4	ZONES 5 – 12	ZONES 13 – 17	ZONES 18 – 20	NEA	HALON	TOTAL
BASELINE NEA SYSTEM	HALON	HALON	HALON	HALON	–	2360 LB	2360 LB
ALTERNATE NEA SYSTEM							
1	NEA	HALON	HALON	HALON	121 LB	2252 LB	2373 LB
2	NEA	HALON	HALON	NEA	135 LB	2179 LB	2314 LB
3	NEA	NEA	HALON	HALON	302 LB	1898 LB	2200 LB
4	NEA	NEA	HALON	NEA	302 LB	1825 LB	2127 LB

- WEIGHTS INCLUDE AGENT CONTAINER
- BASELINE SYSTEM USED FOR OBIGGS WEIGHT CALCULATIONS

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The results of the C-5B OBIGGS preliminary design revealed that either a PM or MS OBIGGS would have a total weight of about 5000 pounds and occupy a volume of about 100 cubic feet. Trade studies revealed that a smaller inert gas generation (IGG) unit combined with a compressor and high pressure inert gas storage was superior to an OBIGGS sized to provide the maximum inert gas flow rate demanded by the airplane. A comparison, based on study ground rules, of the OBIGGS with the LN_2 system (Table 10) reveals that the weight of the LN_2 system is about 10% higher than the OBIGGS but that the volume required for the LN_2 system is less than 50% of that required by the OBIGGS.

The quantity of 167 pounds of stored NEA required at take off is based on allowing the dive valve to open during an emergency descent provided the oxygen concentration does not exceed 12%. (The current LN_2 system limits the oxygen concentration to less than 9% at all times). Note that the volume of the Halon bottles was not included but the Halon bottle size is generally a minor factor. The 3000 psia storage pressure applies only to NEA storage and not to the stored LN_2 system. For these conditions the weights of the PM and MS OBIGGS are about 10% lower than the LN_2 system but the volumes of the OBIGGS are more than twice as large as the LN_2 volume.

Estimated development and acquisition costs are summarized in Table 11. Although considerable effort was expended to arrive at these estimates, they must be considered preliminary due to the uncertainties in estimating costs of developing new hardware. A direct comparison of a PMIGGS and the LN_2 system is given in Ref. 6. Relevant data were extracted and expressed in terms of 1984 dollars. Since most of the data applied to a KC-135 installation the following assumptions were made:

o the cost of equipment for the C-5B airplane would be a factor of two higher than for the KC-135 airplane; and

o the cost of installing the system on the C-5B airplane would be about the same as for the KC-135 airplane.

Even though the results indicate lower installation costs for the PMIGG and MSIGG systems, the error band on the estimates and the need to add a portion of the development costs to each IGG unit, cause its installation costs to be

TABLE 10.

COMPARISON OF NEA$_5$ AND LN$_2$ SYSTEMS FOR C-5B AIRPLANES

	PMIGG		MSIGG		LN$_2$ SYSTEM	
	WEIGHT	VOLUME	WEIGHT	VOLUME	WEIGHT	VOLUME
GENERATING SYSTEM						
CONDITIONING SYSTEM	115 LB	10.5 FT^3	148 LB	14.2 FT^3	–	–
IGG	275	13.0	375	13.6	–	–
COMPRESSOR AND MOTOR [1>	236	6.2	236	6.2	–	–
STORAGE BOTTLES & MISC PLUMBING [1>	812	64.4	812	64.4	1213 LB	40 FT^3
STORED GAS (AT TAKEOFF)	167	–	167	–	1500	–
HALON	2360	[2>	2360	[2>	1898	[2>
SCRUB AND PRESSURIZATION SYSTEM HARDWARE	1059	[2>	1059	[2>	1059	[2>
TOTAL	5024 LB	94.6 FT^3	5157 LB	98.4 FT^3	5670LB	40 FT

NOTES:

- OBIGGS FOR FUEL TANK INERTING ONLY

    [1>   3000 PSIA

    [2>   NOT CONSIDERED

TABLE 11.

ESTIMATED DEVELOPMENT AND AQUISITION COSTS FOR C-5B AIRPLANES

	PMIGG		MSIGG		LN$_2$
	DEVELOPMENT	PER AIRPLANE	DEVELOPMENT	PER AIRPLANE	PER AIRPLANE
CONDITIONING SYSTEM	$3,009	$66.6	$2,948	$65.3	—
IGG AND HARDWARE	NONE REQUIRED	57.3	NONE REQUIRED		—
COMPRESSOR AND MOTOR	580	48.0	580	48.0	—
STORAGE BOTTLES (2 REQUIRED)	300	30.4	300	30.4	$335.0
INSTALLATION	—	255.0	—	255.0	205.0
SUPPORT EQUIPMENT	—	—	—	—	45.0
TOTAL	$3,889 K	$457.3 K	$3,828 K	—	$585.0 K

NOTES:

- BASED ON 100 SHIPSETS, 1984 DOLLARS

- OBIGGS FOR FUEL TANK INERTING ONLY

  $\triangleright$ ESTIMATE NOT AVAILABLE

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only approximate. Therefore, the appropriate conclusion is that the installation costs of the three systems would be similar.

Operating costs are summarized in Table 12. Since the bleed air requirements for the IGG systems are well-defined, the operating costs associated with bleed air extraction can be defined quite accurately. However, the maintenance costs for the IGG systems are projections based on limited ground operation. The costs for the LN_2 system are based on in-service experience.

Clearly, the cost of the LN_2 is the key cost when comparing the OBIGGS and LN_2 systems. As noted, LN_2 costs are based on a delivered price of 8 cents per pound. The cost of the LN_2 system does not include costs of providing LN_2 at additional air bases.

Finally, the life cycle cost estimates for OBIGGS and LN_2 systems are presented in Table 13. The significant difference in operating costs, primarily LN_2 costs, is directly reflected in the life cycle costs. Therefore, cost as well as logistics benefits accrue from using the OBIGGS on large aircraft similar to the C-5.

TABLE 12.
ESTIMATED OPERATING COSTS ($ / FLIGHT HOUR) FOR C-5B AIRPLANES

	PMIGG	MSIGG	LN$_2$
FUEL BURN TO CARRY AVG WEIGHT	$33.74	$34.60	$33.89
COST OF LN$_2$	–	–	$37.20
LN$_2$ SERVICING AND STORAGE	–	–	$4.78
BLEED AND RAM AIR PENALTY	$4.73	$7.36	–
POWER EXTRACTION	$3.84	$3.69	–
MAINTENANCE	$0.42	$0.42	$1.63
TOTAL	$42.73 /fh	$46.07 / fh	$77.50 /fh

ASSUMPTIONS :

- LABOR $8 /HOUR
- COST OF FUEL $0.20 /LB
- COST OF LN$_2$ $0.80 /LB
- COST OF LN$_2$ LOST IN BOIL-OFF AND SPILLAGE INCLUDED (4 LB LOST PER LB USED)
- AVERAGE COST OF WEIGHT   3.24 LB – FUEL / HOUR PER 100 LB – ADDED WEIGHT

TABLE 13.

ESTIMATED LIFE CYCLE COST COMPARISON FOR C-5B AIRPLANES

COST PER AIRPLANE	PMIGG	MSIGG	LN$_2$
ACQUISITION COST (DOLLARS)	$457 K	?	$585 K
OPERATING COST (DOLLARS)	$1,257 K	$1,356 K	$2,281 K
TOTAL LIFE CYCLE COST	$1,714 K	?	$2,866 K
SAVINGS, PER AIRCRAFT	$1,152 K	?	—

ASSUMPTIONS :

- AVERAGE FLIGHT LENGTH   4.8 HOURS
- AIRPLANE LIFE   20 YEARS
- UTILIZATION   800 HOURS / YEAR
- INFLATION   6% / YEAR
- 1984 DOLLARS

4.0 DEVELOPMENT OF ADVANCED FIGHTER OBIGGS DESIGN

Fuel tank fire protection is a key requirement for the Advanced Tactical Fighter (ATF) airplane under development by the Air Force. Currently, explosion suppressant foam and Halon are used for fighter airplane fuel tank protection. A discussion of disadvantages of these systems is given in Section 1.0. The primary objective of this portion of the study was to investigate the feasibility of using OBIGGS for ATF fuel tank fire protection. The potential extension of the OBIGGS for dry bay fire protection was also considered.

4.1   Ground Rules

Generic ATF configurations and missions were selected for this unclassified study. The airplane configuration and missions were based on those resulting from the Propulsion Assessment for Tactical Systems (PATS) study (Ref. 10). The basic ground rules were to:

o provide full time inerting for the most severe of six candidate PATS missions including emergency descents at any time in the mission;

o design for standard day operation;

o design for JP-4 fuel; and

o consider the impact of dry bay fire protection in determining nitrogen enriched air (NEA) quality requirements.

Trade-off studies included:

o a stored NEA gas system versus a demand system;

o a comparison of molecular sieve and permeable membrane air separation modules; and

o a comparison of OBIGGS fire protection with liquid nitrogen, Halon, and foam.

Full time inerting implies limiting the oxygen concentration in the fuel tank vapor space (ullage) to less than 9% at all times. While this requirement is satisfied for most of the mission, a temporary relaxation of this requirement during airplane taxi time was required to prevent the OBIGGS from becoming excessively large. The candidate PATS missions were analyzed in terms of flight segments with high inert gas demands. This evaluation led to the appropriate mission for OBIGGS sizing.

Although the ground rules specify JP-4 fuel, the differences between JP-4 and kerosene type fuels such as JP-8 could impact the OBIGGS design. For example, the concentration of fuel vapor in the ullage reduces the quantity of inert gas required to maintain the oxygen concentration at less than 9%. Although the vapor pressure of JP-8 is insignificant at fuel tank temperatures of interest, the concentration of JP-4 vapors, especially at higher temperatures, could be significant. The solubilities of oxygen and nitrogen in the two fuels are also different; this solubility difference impacts fuel scrubbing requirements (Section 4.3.2).

The use of an inerting system to provide dry bay fire protection has been developed for the C-5 airplane (see Section 3). One aspect of the current study was to determine if a similar approach, using the OBIGGS for ATF dry bay fire protection, was feasible.

4.2 Mission Analysis

As mentioned, ATF configurations used in the Propulsion Assessment for Tactical Systems (PATS) study were used for this study. The six missions required by the ground rules were investigated; the down selection process yielded the baseline air-to-air and baseline air-to-ground systems shown in Figures 38 and 39, respectively.

The baseline air-to-air mission was characterized by a Mach 0.9 cruise at 46,000 feet followed by target penetration at Mach 1.8 at 52,000 feet. The mission radius was 442 nautical miles with a 177 nautical mile penetration radius. This mission had a gross weight of 40,000 pounds and a payload of 2160 pounds. The configuration for the low altitude air-to-ground mission had a higher gross weight, 42,950 pounds, and more than twice the payload, 5110

Baseline mission	Baseline configuration

Gross weight = 40,000 lb
Payload = 2160 lb
MPEN = 1.80

57 K'
54 K'
52 K'
46 K'
20 K'
M 0.4
177 NMI
MACH
1.8
265 NMI
MACH 0.9
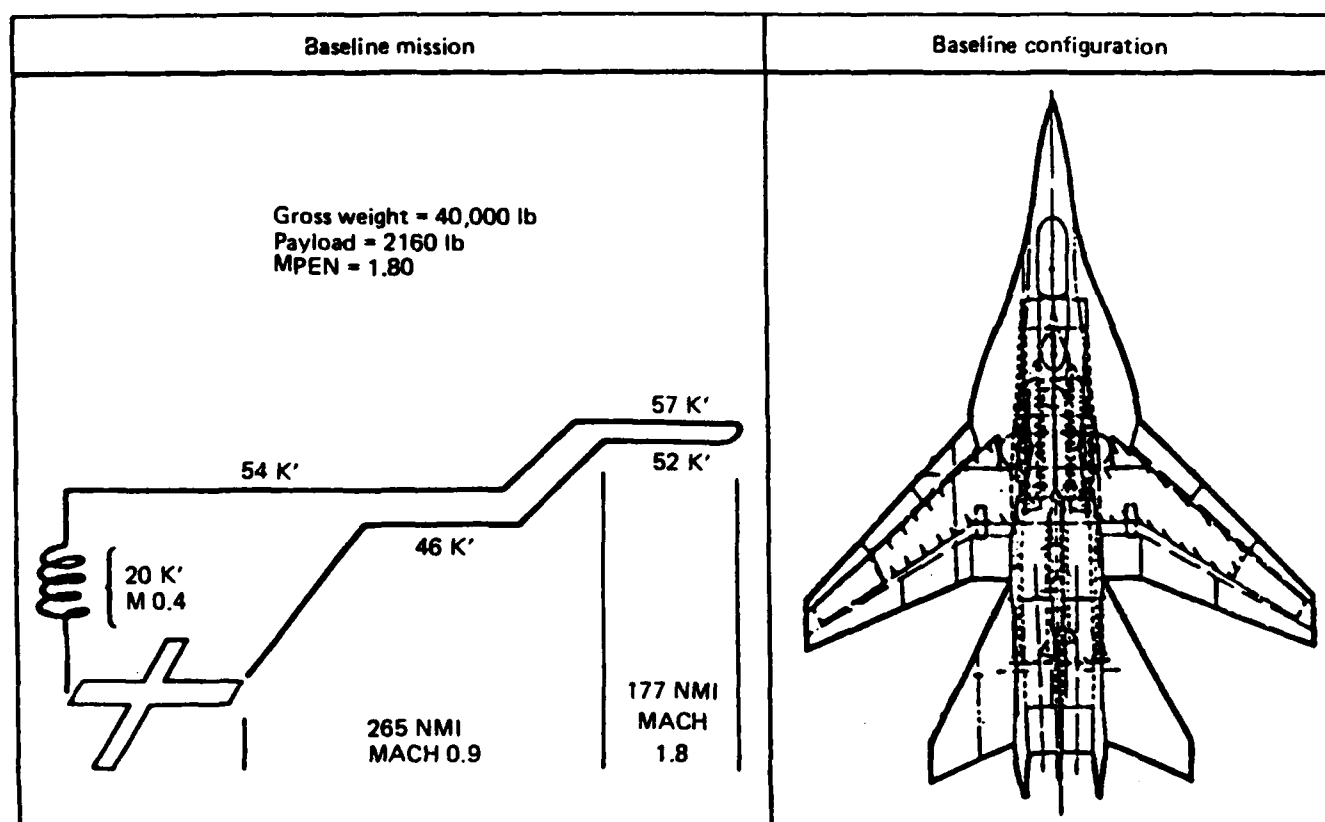
Figure 38 Air -to-Air Baseline System

Baseline mission	Baseline configuration

- Gross weight = 42,950 lb
- Payload = 5110 lb
- MPEN = 0.90

54 K'

45 K'

20 K'
M 0.4

0.2 K'

107 NMI
MACH
0.9

322 NMI
MACH 0.9
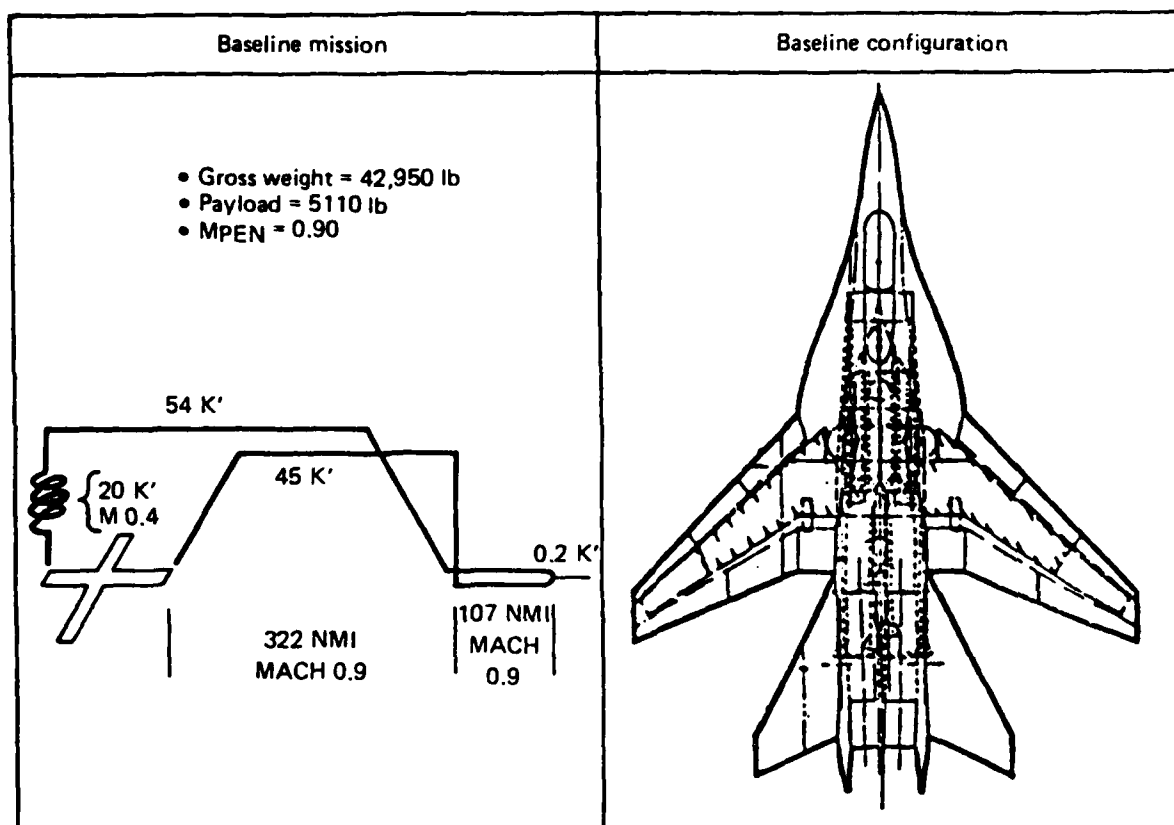
Figure 39 Low Altitude Air-to-Ground Baseline System

pounds. The mission radius of 429 nautical miles with a 107 nautical mile
penetration radius was similar to the air-to-air mission but completely
subsonic. For the design mission, 1941 gallons of fuel was loaded into the
2000 gallon total volume fuel tanks.

A prerequisite in establishing mission inert gas requirements was to determine
whether a stored gas or a demand system was superior for the missions in
question. This decision did not require a detailed trade-off study for this
airplane. An examination of the descent rates revealed that very high
production rates of NEA would be required if a demand system was used for tank
repressurization. The weight and volume of current technology air separation
modules would place an inordinately large penalty on the airplane, based on
engineering judgement. Therefore, a stored gas system was specified for this
fighter OBIGGS study.

In a stored gas system, the gas is assumed to be generated at a constant
rate. Generating inert gas at a constant rate implies that the supply air is
at a constant total pressure and temperature regardless of airplane flight
conditions and engine power settings. ECS equipment with the potential to
produce constant supply air conditions is state-of-the-art. The key reason
for a constant generation rate is that the compressor in the stored gas system
requires a constant inflow for best performance. If the inflow is less than
compressor capacity, the compressor would be oversized and result in an
unnecessary weight penalty. Therefore, the number of descents becomes the key
sizing factor since every descent requires fuel tank repressurization from the
inert gas storage tank. The subsonic air-to-ground mission was the design
mission for this study because two descents were required, one for low
altitude penetration to the target and the other upon returning to its base.
The supersonic mission with its high altitude penetration has only one descent
(return to base.)

4.3 Advanced Fighter OBIGGS Preliminary Design

A realistic OBIGGS preliminary design was essential in comparing the
performance and penalties of the OBIGGS with other fire protection systems.
The oxygen concentration in the inert gas was one important consideration.

Since the oxygen concentration increases with inert gas flow rate, the optimum combinations of NEA flow rate and oxygen concentration were sought. Another consideration was the effect of various inert gas requirements on system sizing. In a stored gas system, the scrub gas flowrate required for climb scrubbing dictates the amount of stored gas which must be available from the previous flight, whereas the descent repressurization requirements establish the generation rate of inert gas and the size of storage bottles required. System size and inert gas generation rate requirements establish the volume, weight, and performance penalties of the system. Finally, since proper OBIGGS performance depends on supply air at carefully controlled pressures and temperatures, the engine bleed air must be processed by an environmental control system (ECS). The additional components and ECS changes required for producing OBIGGS supply air must be included as part of the penalty of the OBIGGS. These preliminary design factors are discussed in more detail in the following sections.

4.3.1 Selection of NEA Oxygen Concentration

Acceptable NEA oxygen concentrations range from near 0% to 9%. However, production of NEA with 9% oxygen is usually unacceptable because there is no safety margin; production of NEA with oxygen concentrations approaching 0% is also unacceptable because the flowrate is very low. Based on previous experience, NEA_5 (5% oxygen) or NEA_7 (7% oxygen) are the best candidates for an optimum NEA oxygen concentration. A study was made to determine the relative merits of NEA_5 and NEA_7; the results are summarized in Table 14. Since the NEA_7 system uses a smaller air separation module (ASM) and ECS, there is an apparent weight benefit associated with the NEA_7 system. However, to achieve the same fuel scrubbing as NEA_5, the NEA_7 system must store 50 percent more scrub gas. Thus, most of the weight benefit is negated. Furthermore, since the dry bay fire protection requirements are based on continuous mixing of incoming NEA with existing compartment gases, 50 percent more NEA_7 is required to meet dry bay fire protection requirements. Some other disadvantages of NEA_7 include:

o The NEA_5 system with a two bottle gas storage system would provide a safe ullage at the end of descent even if one bottle was damaged or inactive; a similar NEA_7 two bottle system would lead to an oxygen concentration higher than the 9% safe level.

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Table 14 NEA₅ and NEA₇ Comparison

	NEA$_5$	NEA$_7$
• Climb scrub efficiency	6 lb req'd @ 0.3 PPM	9 lb req'd @ 0.45 PPM
• Dry bay protection requirement	≈ 0.32 lb/ft^3	≈ 0.47 lb/ft^3
• Maximum ullage O₂ concentration at end of descent with only 1/2 of stored gas available	8.1%	9.7%
• Feasibility of ullage gas refuel scrubbing schemes	GOOD	POOR
• Net system weight increase	Only 3% (5 lbs)	–

o the feasibility of using the ullage gases for subsequent refuel scrubbing is poor.

Finally, the weight of the two systems are similar with the NEA_5 system being slightly heavier. The overall superior capability of the NEA_5 system more than offsets its minor weight disadvantage; therefore, the NEA_5 system was chosen for the subsequent OBIGGS design study.

4.3.2 Scrub Gas Flow Requirements

The quantity of scrub gas required for this ATF study was based on evaluating ullage oxygen concentrations using scrub gas flowrate as a parameter and making several key assumptions, including:

o standard day operation;
o JP-4 fuel;
o 5% NEA scrub gas;
o 15 minutes taxi time prior to take-off;
o a climb valve setting of 6.4 psig;
o a demand regulator setting of 4.7 psig;
o atmospheric fuel tank venting prior to take-off; and
o ullage oxygen concentrations could exceed 9% during the airplane taxi phase.

Standard day atmospheric properties and JP-4 fuel were assumed consistent with study ground rules. Since constant supply air properties were assumed, hot and cold day effects would be manifest as changes in ECS power requirements. Quantifying these effects was not included in this study. The NEA quality of 5% for the scrub gas was based on the trade-off study (Section 4.3.1) which showed that 5% NEA was the best compromise between NEA flowrate and quality. The 15 minute taxi period provided time for fuel scrubbing to ensure safe ullage oxygen concentrations prior to take-off. The climb valve setting of 6.4 psig was based on the F-16 tank pressurization schedule and established maximum fuel tank overpressures. After fuel scrubbing was terminated, the demand regulator system maintained a specific fuel tank pressure while allowing for fuel depletion and repressurization during mission descents. For this study, scrub gas flowed whenever the tank pressure was less than

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4.7 psig. Atmospheric fuel tank venting was assumed during refueling. Since scrubbing is more effective on the ground with atmospheric venting, it was assumed that the climb valve remained open until take-off.

The results of the scrubbing analysis are summarized in Figure 40. Ullage oxygen concentrations are shown for scrub flowrates of 0.2, 0.3, and 0.4 pounds per minute (PPM). In the case of the 0.3 pounds per minute scrub flow, results are presented for both an ullage which was initially inert (following a previous flight) and an ullage initially filled with air (following fuel tank entry for inspection or maintenance). The initial oxygen concentration is less than the value of 21% for an air-filled ullage because fuel vapor in the ullage reduced the oxygen and nitrogen partial pressures.

Several important conclusions can be drawn from the results in Figure 40. First, even with an initially inert ullage, scrubbing the fuel caused relatively high oxygen evolution, producing ullage oxygen concentrations temporarily exceeding the 9% safe limit, unless extremely high scrub flowrates were used. Allowing the ullage oxygen concentration to exceed 9% during taxi at the home base of the airplane was considered to be an acceptable risk, since a larger and heavier OBIGGS would have been required to maintain less than 9% during the taxi phase. Second, since the amount of oxygen scrubbed from the fuel is proportional to the oxygen concentration in the fuel, the oxygen removal rate is greatest just after scrubbing is initiated and decreases thereafter. This rate difference is evident in the curves for an initially inert ullage; all the curves peak at a value of about 15%, but the time required to reach the peak value varies inversely with scrub flow rate. (These curves suggest that a less efficient scrubbing technique perhaps combined with ullage washing could reduce the peak oxygen concentration during the early portion of the fuel scrubbing phase.)

The sharp decrease in oxygen concentration at takeoff is due to the increase in tank pressure caused by closing the climb valve. Since the analysis assumes local equilibrium between the ullage gases and dissolved gases, pressurizing the tank with NEA_5 causes the equilibrium ullage oxygen concentration to decrease. As the airplane climbs out, the demand regulator terminates the flow of scrub gas, and the climb valve opens to vent ullage gases. The result is a gradual rise in ullage oxygen concentration as shown
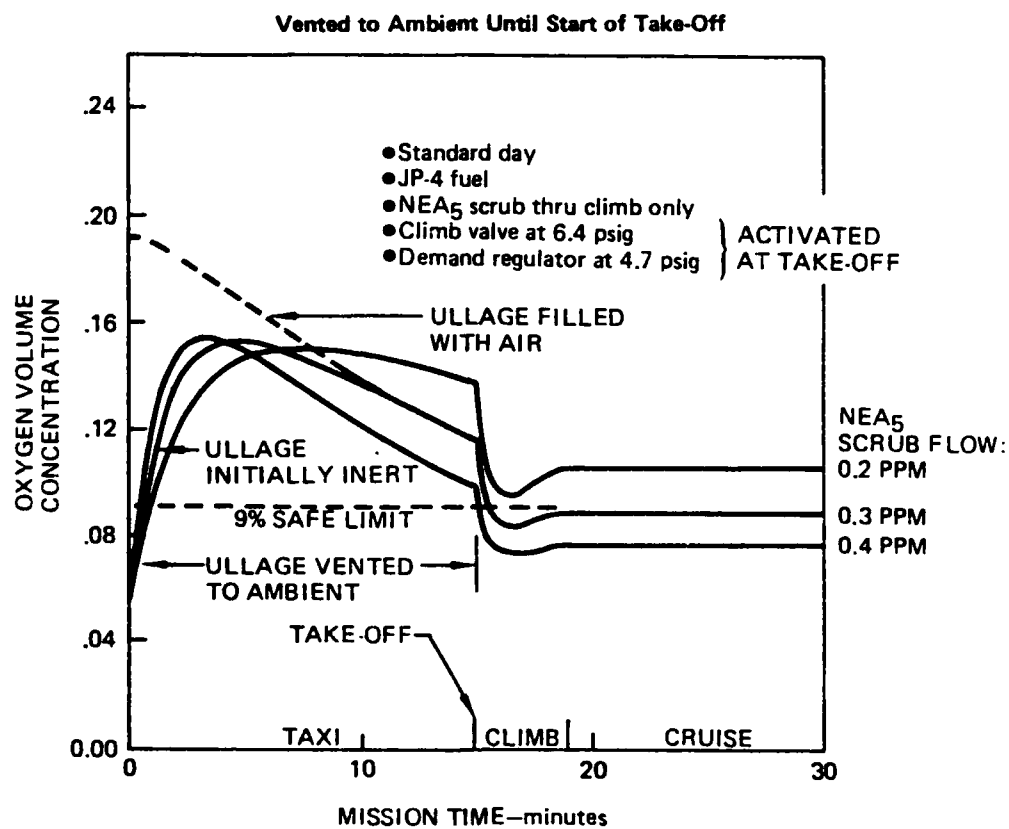
Figure 40 *Ullage O₂ Concentration vs Scrub Flowrate*

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in Figure 40. In this analysis, no scrubbing was assumed for the cruise portion of the mission. Therefore, the ullage oxygen concentration remains constant as shown. The analysis reveals that a 0.3 pounds per minute scrub gas flowrate is appropriate for this ATF study. This rate suffices for a tank initially filled with air as well as an initially inerted tank provided that oxygen concentrations above 9% are allowed during the airplane taxi phase.

4.3.3 OBIGGS Sizing

The two fundamental sizing factors are:

o   the inert gas generation rate must be adequate to provide inert gas for an unplanned or emergency descent at any point in the mission; and

o   the storage tank volume must be adequate to contain the inert gas required for final fuel tank repressurization plus the gas required for scrubbing the fuel for the subsequent mission.

The first sizing factor is illustrated by the short dashed line in Figure 41, which shows the quantity of inert gas required for an emergency descent at any point in the planned mission. In this case, the sizing point is given by an emergency descent just after the climb to about 45,000 feet about 80 minutes into the mission. (Note that for a stored gas system the rate of descent is not a crucial variable; the distribution lines and demand regulator would simply have to be sized for the peak flowrate requirements. Conversely, for a demand system the flowrate requirement during a high speed descent is often the key sizing factor for the air separation modules).

The second sizing factor (the storage tank volume) is also illustrated in Figure 41 by the requirements at the end of the mission. A total of 11.5 pounds of inert gas is required for the final descent. In addition, 6 pounds of stored gas is required for fuel scrubbing for the next mission, for a total required storage capacity of 17.5 pounds.

The time line for the ATF OBIGGS design mission (Figure 42) is fundamental to establishing inert gas requirements. Even the taxi time is important for an OBIGGS using a high pressure inert gas storage system because the size of the
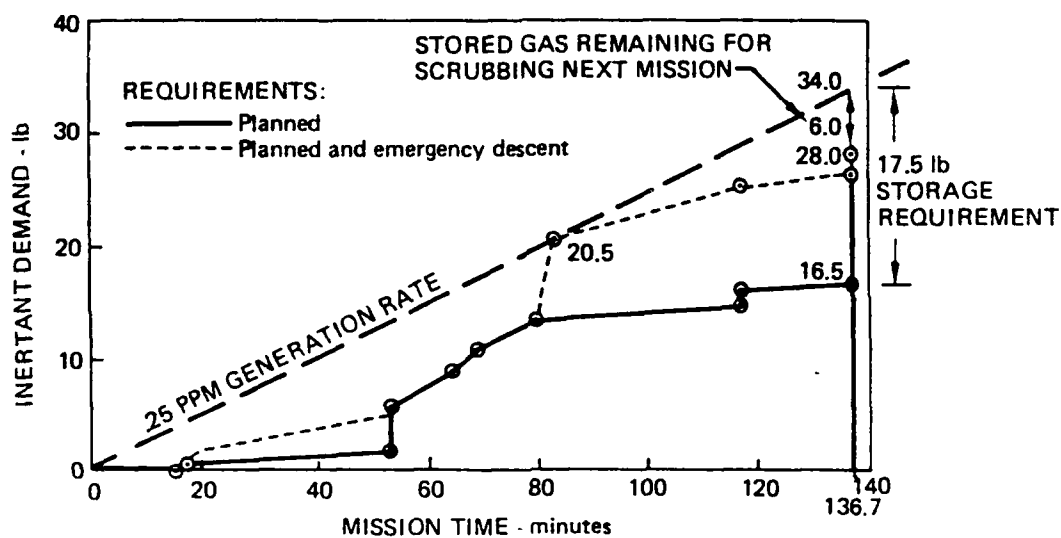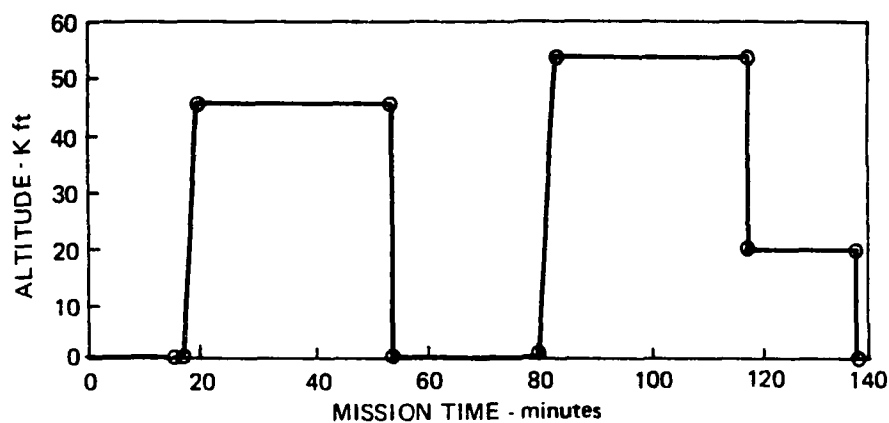
Figure 41 Fighter Air-to-Ground Mission Inert Gas
Requirements — Standard Day

Baseline mission

- Gross weight = 42,950 lb
- Payload = 5110 lb
- MPEN = 0.90
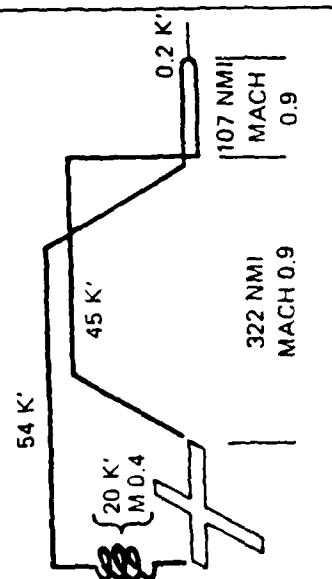
Time-altitude profile

Segment	Time (minutes)	Altitude (K ft)	Fuel used (gallons)	Ullage size (gallons)
Taxi	15.0	0.0	102	161
Take-off	16.0	0.0	169	228
Climb	18.7	45.4	286	345
Cruise	52.5	45.4	567	626
Descent	53.4	0.2	572	631
Cruise	64.3	0.2	895	954
Turn allowance	68.3	0.2	1090	1149
Cruise	79.2	0.2	1397	1456
Climb	82.2	53.8	1497	1556
Cruise	116.0	53.8	1700	1759
Descent	116.7	20.0	1704	1763
Loiter	136.3	20.0	1825	1884
Descent	136.7	0.0	1827	1886
			(1921 useable fuel)	(2000 tank volume)

Figure 42 Timeline for Design Mission

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OBIGGS is inversely related to the time available for generating inert gas. Another key factor is the structural limitation of the fuel tanks. Obviously, if the tanks could withstand underpressures of about one atmosphere, repressurization could proceed at a leisurely pace, and the OBIGGS design would be greatly simplified. Since flight-weight fuel tanks typically have a maximum underpressure design limit of about 5 psig, the repressurization rate is an important design factor in sizing the OBIGGS.

Several key factors of OBIGGS sizing emerge from examining the time line. The taxi time, while very beneficial for a stored gas system, is of no consequence for "demand systems" (systems which must supply inert gas flow from the air separators on demand for tank pressurization or fuel scrubbing). Since climb out to cruise altitude requires ony 2.7 minutes, fuel scrubbing must remove dissolved oxygen in a well-controlled manner, i.e., remove the oxygen at a rate such that safe levels occur throughout climb and cruise. To find the inert gas generation rate, a straight line, representing a constant generation rate, is constructed from the origin through the point corresponding to the most severe of the two sizing factors (the long dashed line in Figure 41). In this study the appropriate generation rate was 0.25 pounds per minute. It was strictly coincidental that the generation rate line passed through both sizing points in the current study; in general the line will not.

4.3.4 ECS Design

The performance of the air separation modules is highly dependent on the temperature and pressure of the supply air. As such, the supply air must be properly conditioned to provide the desired NEA output. This conditioning is achieved by extracting bleed air from the engine compressor and further conditioning the air as required, using typical environmental control system (ECS) equipment.

The proposed ATF OBIGGS and oxygen gas generation (OGG) system is shown in Figure 43. The Boeing ATF ECS configuration consists of a closed loop air cycle refrigeration system and a liquid heat transport loop. Bleed air is extracted from the engines to pressurize the closed air loop and supply makeup air. Air at 75 psia and 75°F maximum will be available from the ECS airframe-mounted accessory drive (AMAD) air compressor for the IGG air supply system.
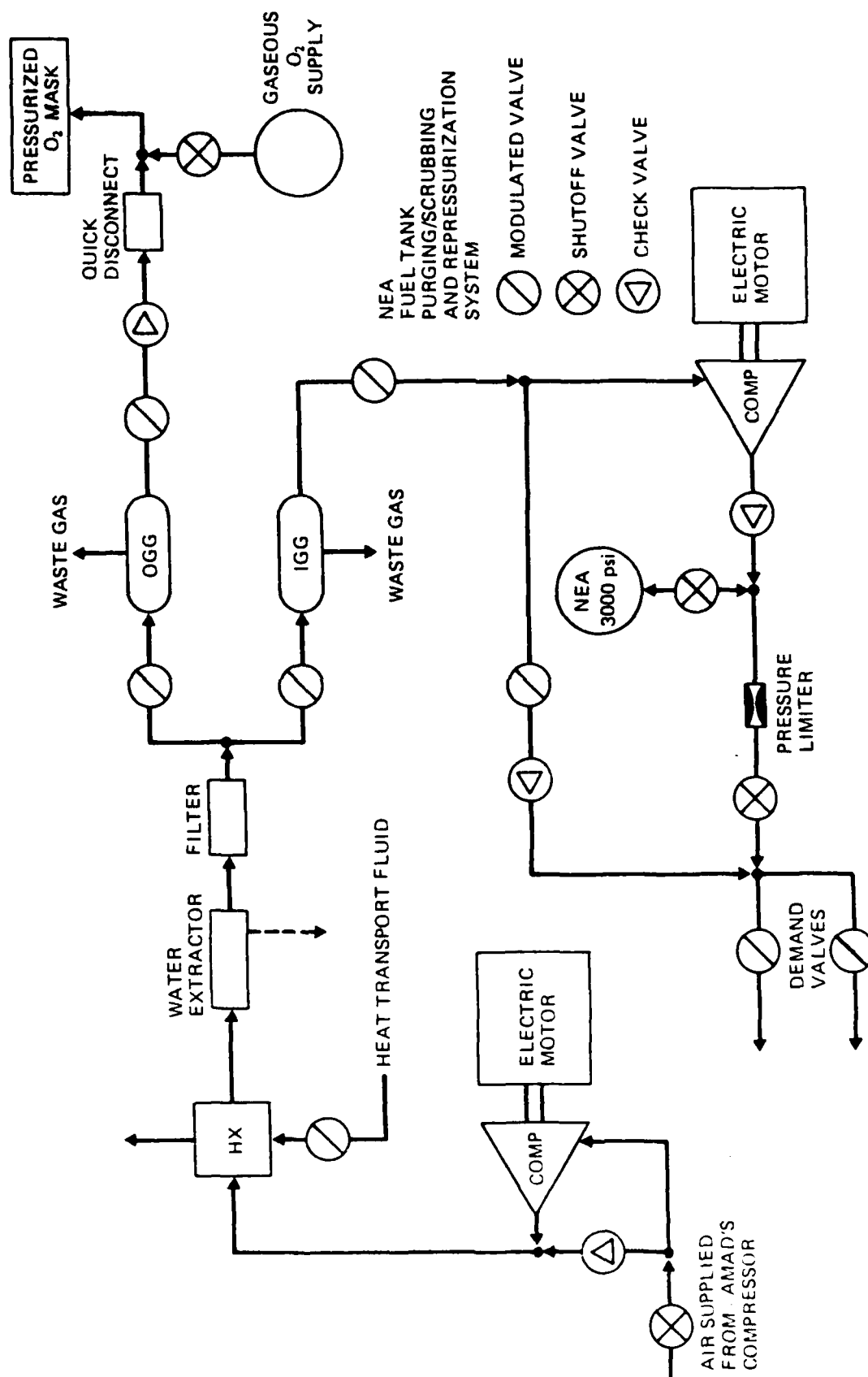
Figure 43 On-Board Fuel Inerting and Breathing Oxygen Generation Systems Schematic

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The optimum pressure requirement for a current technology permeable membrane inert gas generator (PMIGG) is about 100 psig. Since the ECS AMAD air compressor is not capable of producing this pressure level, an additional boost compressor could be used. An alternative would be to increase the size of the PMIGG and reduce the inlet pressure to 75 psig. This alternative would allow a smaller boost compressor and reduce the operating time of the compressor since the AMAD supplies air above 75 psig at most mission points. This approach, a larger PMIGG, was selected for the baseline system. An air to liquid heat exchanger cools the air by utilizing the ECS heat transport loop which transfers heat to a ram air/fuel heat sink. A water extractor and filter remove water and dust particles from the air. The pressure regulator controls inlet air pressure at the IGG to 75 $\pm$5 psig. The temperature is controlled to 75 $\pm10^{o}F$ at the IGG interface.

The pressure requirement for the molecular sieve inert gas generator (MSIGG) is 65 psia; therefore, the boost compressor and check valve shown in Figure 43 are not required. The pressure regulator would be set at 50 $\pm$5 psig and temperature control set at 65 $\pm10^{o}F$. The air supply system for the MSIGG is otherwise the same as the PMIGG system except for size.

The inert gas generator (IGG)/ECS interface conditions are given in Table 15 for both the PMIGG and MSIGG. The resources needed to supply air at the required conditions are also shown.

TABLE 15. ATF IGG AIR SUPPLY SYSTEM PERFORMANCE

	PMIGG	MSIGG
• IGG/ECS INTERFACE		
FLOW RATE TO IGG ∿ LBS/MIN	1.0	1.6
PRESSURE ∿ PSIG	75 +5	50 +5
TEMPERATURE ∿ DEG. F	75 +10	65 +10
• RESOURCES REQUIRED		
BLEED AIR ∿ LBS/MIN	1.05	1.65
POWER ∿ KW	.50	0
LIQUID FLOW ∿ LBS/MIN	2.10	3.35
% ATF BLEED AIR EXTRACTION	5.8	9.2
% ATF CLOSED LOOP ECS AIR EXTRACTION	1.7	2.7
% LIQUID LOOP FLOW	0.7	1.0

The performance data indicate that in addition to the penalties for the IGG dedicated equipment, there is also a penalty associated with an increase in ECS size to accommodate the IGG requirements. The bleed air system must be increased by 5.8%, and the closed loop refrigeration system increased by 1.7% for the PMIGG. There is also an engine power extraction penalty chargeable to the IGG ATF supply system. The engine bleed air is compressed in the AMAD compressor in the ATF baseline system. Since a percentage of this compressed air is extracted for IGG usage, this air becomes an IGG chargeable penalty. This loss amounts to about 1.8 hp for the PMIGG air source and 2.7 hp for the MSIGG. These losses were taken into consideration when the penalties were calculated.

The estimated ATF penalties for weight and theoretical specific fuel consumption (Δsfc) are shown in Table 16.

TABLE 16. ATF PENALTIES*

$$\frac{\text{CHANGE IN TAKE-OFF GROSS WEIGHT}}{\text{CHANGE IN OPERATING WEIGHT}} \quad \sim 4.1$$

CHANGE IN AIRPLANE SIZE FOR 1% CHANGE IN SFC

PENETRATION ∿ 0.245%

CRUISE   ∿ 0.177%

LOITER   ∿ 0.05%

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The estimated weights for the PMIGG and MSIGG air source supply system is shown in Table 17. The estimated weights are 19 and 17 pounds, respectively, for the PMIGG and MSIGG systems. This estimate does not include the additional weight for the increase in the ATF ECS size to accommodate the IGG requirements. The IGG requirement adds 22 pounds to the PMIGG air source for a total operating weight increase of 41 pounds. The corresponding weights for the MSIGG are 25 pounds and 42 pounds.

Table 18 shows a breakdown of penalties for the ATF/PATS air-to-ground Mission. The total calculated fuel penalties were 211.8 pounds ΔTOGW for PMIGG and 229.8 pounds ΔTOGW for MSIGG.

The estimated size of the PMIGG air supply system is 18" x 8" x 5" or .42 cu. ft. The estimated size of the MSIGG air supply system is 15" x 7" x 5" or .30 cu. ft. For both systems, the air duct is 3/8 inch in diameter, and the heat transport fluid line is 1/4 inch in diameter.

The estimated costs for the IGG air supply system are shown in Table 19. Development and production costs are based on a minimum of 100 shipset quantities and all costs are in terms of 1984 dollars. The costs were estimated by Tsujikawa (Ref. 11) based on estimates from vendor inputs, experience in developing similar systems and engineering judgement. Particular attention was given to relative values to help ensure that trends would be meaningful.

4.4 Comparison Studies

To establish the viability of an OBIGGS for fuel tank inerting on ATF airplanes, both technical and economic evaluations were made. These evaluations included comparing molecular sieve and permeable membrane air separation modules for the OBIGGS concept as well as comparing foam, liquid nitrogen, and Halon inerting with the OBIGGS.

TABLE 17. ESTIMATED ATF IGG AIR SUPPLY SYSTEM WEIGHTS

	QUANTITY PER APL.	PMIGG WEIGHT (LBS)	MSIGG WEIGHT (LBS)
• SHUTOFF VALVE	1	1.0	1.3
• BOOST COMPRESSOR	1	1.8	-
• MOTOR	1	1.8	-
• CHECK VALVE	1	.4	-
• HEAT EXCHANGER	1	1.3	1.6
• MODULATING VALVE	1	1.1	1.3
• TEMPERATURE SENSOR	1	.12	.12
• WATER EXTRACTOR	1	1.3	1.3
• FILTER	1	1.0	1.1
• PRESSURE REGULATOR	1	1.25	1.25
• TEMPERATURE CONTROLLER	1	.50	.50
• DUCTING AND TUBING	1	2.5	3.5
• WIRING	1	2.0	2.0
• THERMOSTAT, COMPRESSOR DISCHARGE	1	.12	.12
• INSTALLATION	1	3.1	2.7
TOTAL WEIGHT		19	17

TABLE 18. TOGW PENALTIES FOR ATF MISSION "C"

	PENALTY ∿ LBS FUEL	
	PMIGG	MSIGG
• BLEED AIR	17.0	27.2
• FAN AIR	6.8	11.8
• POWER EXTRACTION	20.0	19.6
• WEIGHT - ECS & CONTROLS	168.0	172.0
TOTAL TOGW	211.8	229.8

TABLE 19. ESTIMATED ATF IGG AIR SUPPLY SYSTEM COSTS

COMPONENT	PMIGG		MSIGG	
	DEVELOPMENT COSTS ($1000)	PRODUCTION UNIT COSTS ($)	DEVELOPMENT COSTS ($1000)	PRODUCTION UNIT COSTS ($)
• SHUTOFF VALVE	50	2500	50	2500
• BOOST COMPRESSOR	250	6000	-	-
• MOTOR	110	2500	-	-
• CHECK VALVE	75	600	75	600
• HEAT EXCHANGER	300	4000	300	4000
• MODULATING VALVE	110	1800	110	1800
• TEMPERATURE SENSOR	40	300	40	300
• WATER EXTRACTOR	15	150	15	150
• FILTER	8	400	8	400
• PRESSURE REGULATOR	150	3000	150	3000
• TEMPERATURE CONTROLLER	150	5500	150	5500
• THERMOSTAT, COMPRESSOR DISCHARGE	40	300	40	300
• DUCTING, WIRING, INSTALLATION, & TEST	700	13500	520	9300
	1998	40550	1458	27850

4.4.1 Molecular Sieve versus Permeable Membrane OBIGGS

The molecular sieve (MS) and permeable membrane (PM) OBIGGS are similar in many respects. One of the primary differences, as discussed in Section 4.4, is that a boost compressor was required for the permeable membrane OBIGGS. Yet, when the preliminary designs of the two systems are compared (Table 20), the systems have almost the same weight, volume, and performance penalties.

Since the performance characteristics and penalties of the MS and PM OBIGGS were comparable, whether the PM or MS OBIGGS was the better choice for the ATF OBIGGS was not clear. The PM OBIGGS was selected for this study and for comparison with other fire protection systems because of the assumption that the PM OBIGGS would have greater reliability and lower maintenance costs.

4.4.2 Comparison of OBIGGS with Other Inerting Systems

Weight, volume, and performance penalties of explosion suppressant foam, liquid nitrogen inerting, and Halon inerting are compared with the OBIGGS in this section. All of the former are viable fuel tank fire protection concepts but have features which make them unattractive for ATF application. The foam presents operational problems as discussed in Section 1 whereas the liquid nitrogen and Halon systems require resupply on the ground between flights. Providing cryogenic facilities or Halon in sufficient quantities at each ATF operational base may create unacceptable logistic problems. Nevertheless, comparing the OBIGGS with these other systems provides valuable guidance in system selection.

The weight, volume, and performance penalties of competing systems are compared with the permeable membrane OBIGGS Table 21. Note that the weight penalty for foam is about a factor of 3 higher than the OBIGGS. Although foam offers the advantage of a totally passive system, the advantage is more than offset by the approximately 1300-1500 pounds weight penalty. Conversely, the detailed comparison of the Halon system with the PM OBIGGS revealed that the PM OBIGGS was roughly twice as heavy as the Halon system (see Table 2). Long term Halon 1301, dissolved in fuel, effects on engine fuel control and hot section parts will need considerable evaluation. If the logistic problems could be solved, the liquid nitrogen system would probably become the most attractive system. The liquid nitrogen system is comparable in weight to the PMIGG system and requires significantly less volume.

Table 20 Comparison of MS and PM OBIGGS

	MSIGG		PMIGG	
	Weight lbs	Volume ft^3	Weight lbs	Volume ft^3
• OBIGGS component				
• Air separation module (.25 PPM @ 5% O_2)	30	1.1	34	1.7
• Compressor, motor & controls	35	1.6	35	1.6
• ECS including valves & controls	42	0.5	41	0.6
• Gas storage bottles (18 lbs NEA$_5$)	41	2.9	41	2.9
• Plumbing-scrub & descent repress.	12	-	12	-
• Stored NEA - mission average	9	-	9	-
TOTALS	169 lbs	6.1 ft^3	172 lbs	6.8 ft^3
• Penalties				
• Fixed airplane (maintain performance & payload by off-loading fuel)				
• Unavailable &/or off-loaded fuel	28 gal		28 gal	
• Cruise range penalty (excludes combat portion of mission)	35 N miles (5%)		35 N miles (5%)	
• P.D. airplane (gross weight increase is req'd to maintain range & performance)				
• OBIGGS weight penalty	692 lbs		705 lbs	
• Air bleed & power extraction penalty	58 lbs		44 lbs	
Total gross weight increase	750 lbs (1.7%)		749 lbs (1.7%)	

Table 21 *LN₂, Halon and OBIGGS Inerting System Comparison*

| | LN$_2$ | | Halon 1301 at 30% by volume [1] | | PMIGG | | Foam | |
	Weight	Volume	Weight	Volume	Weight	Volume	Fine 50% void	Coarse 20% void
System components								
Air separation module and compressor	66	1.0			69	3.3		
ECS or heat exchangers for LN$_2$	18				41	0.6		
Valves and controls	54	1.8	12	1.6	41	2.9		
Storage bottle(s)			27					
Plumbing	12		6		12			
Inertant stored-mission average (initial loading: LN$_2$ -36 lb, Halon -75 lb)	16		36		9			
Total	166 lb	2.8 ft^3	81 lb	1.6 ft^3	172 lb	6.8 ft^3		
Penalties								
Fixed airplane (maintain performance and payload by off-loading fuel)								
Unavailable and/or off-loaded fuel	26 gal		13 gal		28 gal		72 gal	84 gal
Cruise range penalty	32 nmi (4.9%)		16 nmi (2.4%)		35 nmi (5.4%)		90 nmi (4.7%)	103 nmi (16%)
PD airplane (increased gross weight to maintain range and performance)								
OBIGGS weight penalty					705 lb			
OBIGGS power extraction penalty					44 lb			
Foam and retained fuel weight							492 lb	575 lb
Total gross weight increase	681 lb (1.6%)		332 lb (0.8%)		749 lb (1.7%)		2018 lb (4.7%)	2357 lb (5.5%)

[1] Air Force test data with a 21% oxygen ullage indicate that a Halon concentration of 20-24% is required to protect against the HEI threat. The 30% Halon concentration was used in this study to allow for ullage oxygen enrichment due to oxygen evolution effects.

4.4.3 Cost Comparisons

The estimated life cycle costs of the various inerting systems were also compared. Establishing the cost elements for the different systems presented several problems. Some costs could be based on actual fleet experience while others were based on cost projections from manufacturer. The costs of providing liquid nitrogen or Halon at all ATF operating bases would be significant but were not included in this study. Experience has shown that the costs of foam based on routine maintenance schedules understate actual costs considerably because of localized in-tank fires and premature foam deterioration. No attempt was made to include these extraordinary costs in this study.

The results of the life cycle cost study are summarized in Table 22. The large life cycle cost advantage of foam is offset by the much higher weight of that system. An additional 1500 pounds represents a considerable weight penalty for an ATF airplane. Several assumptions were made in the study of foam for ATF fire protection. Fuel temperatures up to $150^\circ F$ and tank wall temperatures (not exposed to fuel) up to about $300^\circ F$ were assumed which made current foams unacceptable. Therefore, one basic assumption was that high temperature foams would be developed in time for ATF implementation. Related assumptions were that the weight, fuel displacement and fuel retention characteristics as well as life cycle costs of high temperature foams would be similar to current foams. The PM OBIGGS and liquid nitrogen systems had similar life cycle costs. The cost of the Halon system is much higher than the other systems considered, primarily because of the cost of Halon itself. In summary, the estimated life cycle costs of the PM OBIGGS, especially when considered in the light of the disadvantages of the other systems, are acceptable.

4.5 Resulting ATF OBIGGS Design

An OBIGGS fuel tank fire protection system was developed for an ATF airplane based on representative but unclassified configurations and missions. The key to sizing the OBIGGS for sufficient inert gas flow was the number of descents during the mission. A totally subsonic air-to-ground mission was the most demanding from an OBIGGS viewpoint because it included two planned descents.

Table 22 *Advanced Fighter Life Cycle Cost Estimates — 1984 Dollars*

	LN_2	Halon	PM OBIGGS	Foam
Cost of system	$ 97,000	$ 8,000	$ 84,000	$10,500
Installation cost	60,000	50,000	90,000	1,500
Subtotal	$157,000	$58,000	$174,000	$12,000
Maintenance and operation (dollars per hr)	6.95	113.00	3.40	3.21
Total cost (500 A/P, 500 hr/yr for 10 yrs)	$96M	$311M	$96M	$14M

NOTES:

● Does not include ground handling cost associated with LN_2 & Halon

● LN_2 costs include a 10% boil-off loss (based on Parker-Hannifan data) after delivery

The air-to-air missions studied had less demanding inert gas requirements, although penetration was at supersonic speeds, because the OBIGGS size was based on just one descent.

The ATF OBIGGS was based on a stored inert gas system; an OBIGGS sized to provide the required inert gas flow rates without gas storage (a demand system) was found to be prohibitively large for an ATF application. Since inert gas flow rate and oxygen content are inversely related, a study was made to find the near optimum compromise. The results revealed that nitrogen enriched air with oxygen concentration of 5% (NEA_5) was the appropriate choice.

A detailed study was made of the inert gas requirements for fuel scrubbing. It was found that the goal of full time inerting had to be relaxed during the taxi phase of the mission to prevent excessive scrub flow rates. This relaxed condition was considered an acceptable compromise because the airplanes would be departing from friendly bases. A scrub flow rate of 0.3 pounds per minute was needed for the ATF OBIGGS.

The overall size of the ATF OBIGGS, including the compressor and tank for the stored gas system as well as the air separation modules, was based on ensuring that the quantity of inert gas stored up to any point in the mission was greater than or equal to the inert gas requirements at that point in the mission. A constant inert gas generation rate of 0.25 pounds per minute and a tank which could contain 17.5 pounds of inert gas at 3000 psig were required.

Conditioned air for the separation modules was supplied by a closed loop refrigeration system and a liquid heat transfer loop. Air at 75 psia and $75^\circ F$ was available from the ECS for air separation modules. These conditions were adequate for the molecular sieve IGG but the permeable membrane IGG required higher pressure for satisfactory operation. The inlet pressure selected for the PMIGG was about 90 psig. This pressure was below the 100 psig required for optimum performance, but the 90 psia pressure allowed a smaller boost compressor to be used in conjunction with the airframe mounted accessory drive (AMAD) air compressor to supply air to the PMIGG. The weights, volumes, and penalties of the MSIGG and PMIGG were quite similar; the PMIGG was chosen for the ATF protection systems comparisons because the PMIGG

is a more passive system. The PMIGG itself weighed 172 pounds and occupied 6.8 cubic feet. The PM OBIGGS resulted in a preliminary design airplane gross weight increase penalty of 749 pounds, or a range penalty of 35 nautical miles, if added to an existing airplane.

The PM OBIGGS was compared with explosion suppressant foam, Halon, and liquid nitrogen on a technical as well as economic basis. The OBIGGS weight was about a factor of three less than the foam weight but was roughly twice as heavy as a Halon system. Volume comparisons with foam were not meaningful, but the OBIGGS required greater volume than the Halon and liquid nitrogen systems. Life cycle cost analysis, based on best available data and projections, revealed that the OBIGGS costs would be about seven times higher than foam, would be comparable to liquid nitrogen systems, and would be one-third the cost of the Halon system. The high cost of the Halon system is due to the cost of the Halon extinguishant itself. The life cycle costs do not include costs of transporting liquid nitrogen and Halon to additional airports. Furthermore, the costs do not include unscheduled maintenance and replacement of foam blocks for the explosion suppressant foam system.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Preliminary designs and trade-off studies confirmed that OBIGGS installations provide viable fuel tank fire protection in C-5B and ATF airplanes. One significant conclusion common to both analyses was that a stored gas system is required to satisfy peak inert gas flow requirements; current technology inert gas generators are too large and too heavy for a demand system (a system sized to produce the maximum inert gas flow required for the mission). Another significant conclusion was that no clear choice emerged in either investigation between the PM and MS OBIGGS with respect to system size and weight and airplane penalties. This commonality is somewhat surprising since the air separation techniques, optimum operating conditions, and performance characteristics of the two concepts are quite different. When all factors were considered, the installed performance and penalties were remarkably similar. The PM OBIGGS would seem to have an inherent advantage because it is essentially a passive device. However, other factors such as performance degradation with time and sensitivity to rapid pressurization (see Part 1 of this Volume) mitigated against its advantage of simplicity. The choice between the PM and MS OBIGGS for a given application should consider such factors as reliability, potential air separation module improvements and sensitivity to the operational environment as well as basic performance characteristics.

In choosing between a stored gas and a demand system, it was assumed that a suitable, reliable high pressure compressor was an "off-the-shelf" item. This assumption is not accurate; considerable additional work is required to develop a lightweight, reliable compressor.

Installation costs for a C-5B OBIGGS would be comparable to the LN_2 system currently used. However, operating and life cycle costs would be considerably higher for the LN_2 system because of the cost of liquid nitrogen.

The ATF OBIGGS has clear advantages over competing fuel tank fire protection systems. The OBIGGS saves significant weight compared to an explosion suppressant foam and eliminates the logistics and cost considerations associated with LN_2 and Halon systems.

Several areas of further investigation were suggested by this study. Development of advanced technology air separation modules may allow a demand system to be feasible. Test data from laboratory scale modules reveal that permeable membrane modules with more than a factor of 10 improvement in performance may be available in the near future. The potential near term performance improvement for molecular sieve modules is only about a factor of 1.5 to 2. However, molecular sieve modules may still have a place in stored gas systems because they are much more compatible with the high temperatures encountered in supersonic flight. If a demand system could be developed, the maintenance and reliability problems of the compressor and related equipment could be eliminated. Since the inert gas flowrate requirements are related to overpressure and underpressure limitations of the fuel tanks, a trade-off study between allowable tank pressures and inert gas requirements would be relevant. Little has been done to establish the effect of aerodynamic heating and heat transfer to the fuel from on-board sources on inert gas requirements for tank pressurization. Since fuel temperatures could reach 150^0F and tank wall recovery temperatures could exceed 400^0F, the effect of increased environmental and fuel tank temperatures on OBIGGS performance and inert gas requirements should be investigated. These elevated temperatures would also impact design and performance of other fire protection systems. LN_2 systems would tend to have much higher boil-off rates. Halon containers would have to be redesigned for the high temperature environment. Foams compatible with high temperature fuel tanks are not available although a program to develop such foams is expected to be initiated in the near future.

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LIST OF ABBREVIATIONS AND SYMBOLS

AMAD   Airframe Mounted Accessory Drive

ACM   air cycle machine

APU   auxiliary power unit

ASM   air separation module

ATF   Advanced Tactical Fighter

ECS   environmental control system

FSS   fire suppression system

GN_2 gaseous nitrogen

Halon   halogenated hydrocarbon

IGG   inert gas generator

LN_2 liquid nitrogen

MS   molecular sieve

MSIGG   molecular sieve inert gas generator

NEA   nitrogen-enriched air

          NOTE: a numerical subscript following the acronym "NEA" refers to the volume fraction of oxygen in the NEA

OBIGGS   on-board inert gas generator system

O_2 gaseous oxygen

PM   permeable membrane

PMIGG   permeable membrane inert gas generator

PPM   pounds per minute

PTU   power transfer unit